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ENGINEERING PSYCHOLOGY IN AVIATION AND ASTRONAUTICS

V. G. Denisov and V. F. Onishchenko

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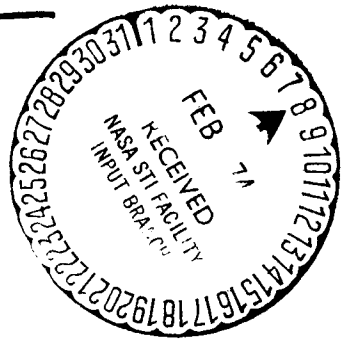

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Annotation

In the book, Doctor of Technical Sciences Professor V. G. Denisov and Candidate in Medical Sciences V. F. Onishchenko have examined problems of the interaction of an operator with a machine, under various operating conditions during flight in aircraft, and they have correlated and analyzed, from the point of view of engineering psychology, experimental data on the operation of aircraft accumulated in recent years. Changes in the psychophysiological capabilities of an operator, as a result of adaptation of the man to the machine and the machine to the man, have been set forth, and the basic theoretical problems in the field of development and application of the man-machine system to aircraft and ways of solving them have been defined.

The book is intended for civil and military aviation engineers and designers, designing aircraft and their equipment. It can be useful to specialists, operating in the fields of engineering, biological and medical cybernetics.

19 tables, 102 illustrations, 79 titles in the bibliography.

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16. Abstract Engineering psychology in design of aircraft and spacecraft is discussed in detail, in determining human psychophysiological traits and capabilities (overt and electrophysiological responses and response times), flight characteristics and control systems, "adjustment" of men and machines into optimum AC systems, citing data from flight, trainer and laboratory experiments. Nature and optimum division between men and machines of data sensing and processing, decision making and control actions is emphasized. Separate chapters treat biomechanical operator-aircraft systems, information models of flight (instrument and controls types and layouts, data coding and display), time-deficit flight (manual to automatic control systems, mainly in landing, takeoff and low-altitude flight), overloads (accelerations, vibrations; use of G-suits, exercises, various types of controls), weightlessness (physiological, operational effects and counteractions -- spacecraft approach and docking as the main example), extravehicular activity (lack of support, friction and orientation; use of special tools, individual capsules and jet units), effects of small space, long, spaceflight isolation, including noise and color effects; ensuring operator reliability and efficiency, use of various trainers and, finally, unsolved problems and areas for future research.

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Foreword

A considerable amount of disconnected experimental and theoretical data has been accumulated up to now, in the field of engineering psychology in aviation and astronautics, both at home and abroad. The time has come to correlate existing data and set it forth from common scientific viewpoints.

Features of the man-machine system in aircraft, psychophysiological capabilities of operators, applicable to various stages of flight, principles and ways to create an information model of flight, controllable flight in a "deficit" and "excess" of time, operation under conditions of overload and vibration, features of the man-machine system under weightlessness, during prolonged flight and in a closed space, with hypodynamia, under conditions of a changed biological medium, in unsupported and unoriented space, are examined in the book. Basic recommendations are set forth on construction of elements of the control system with which the operator interacts, and data are presented on the problems connected with selection and training of aircraft operators for professional activity.

The book is written on the basis of materials contained in monographs and handbooks on general engineering psychology, published at home and abroad, as well as of materials from individual articles by domestic scientists and foreign specialists on problems of aviation medicine and engineering psychology in aviation and astronautics. Soviet specialists in the fields of aviation and space medicine and engineering psychology have done great service in the organization and development of engineering-psychological research, applicable to conditions of atmospheric and space flight.

The authors are aware of the fact that an effort to set forth an exceptionally broad and many-sided group of questions and problems of engineering psychology in aviation and astronautics in one generalized work is a very complicated affair.

This becomes even clearer, if it is taken into account that engineering psychology now is living through a vigorous period of formation, and that engineering psychology in aviation and astronautics is "reaching manhood" together with it: both its subjects and methods are being more clearly defined; the accumulated experimental data are being comprehended theoretically; the volume of further research is being expanded; and larger and larger numbers of a varied cross section of specialists are being included in carrying it out.

Therefore, the book, presented for the judgment of readers, does not pretend to complete treatment of the questions analyzed. Individual positions on them, undoubtedly are not final, and they can serve as reference points for future scientific discussions, and a number of problems are only noted, but not solved.

Translation Editor's Note

The term "aircraft" as used in this translation refers in the broad sense to "flight craft".

List of Abbreviations

AC -- Aircraft or flight craft
CNS -- Central nervous system
EC -- Electronic computer; eye closing
EEG -- Electroencephalogram
EKG -- Electrocardiogram
EMG -- Electromyogram
EO -- Eye opening
GSR -- Galvanic skin response
HNA -- Higher nervous activity
LPD -- Latent period of desychronization
LPS -- Latent period of synchronization
M -- Mach
PG -- Pneumogram
SC -- Spacecraft

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ENGINEERING PSYCHOLOGY IN AVIATION AND ASTRONAUTICS

V. G. Denisov and V. F. Onishchenko

Introduction

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In connection with further growth of the air force and successes in mastering outer space, the provision of optimum interaction of an operator with a machine, under conditions of flight with crews in various aircraft, is beginning to become more and more important. Man-machine control systems in aircraft are very complex, the work of the crews on these craft is exceptionally responsible, and requirements for accuracy and reliability of control systems are continually increasing.

The necessity for a scientific basis for planning and development of the engineering elements of control systems and of the actual systems with operator participation is arising, not only in aviation and astronautics, but in many other fields of activity of human operators: in essence, everywhere where man interacts with a machine which he can control. The new scientific discipline emerging at the "interface" of biological and engineering sciences, "engineering psychology," is concerned with this basis.

Engineering psychology is a branch of psychology, studying the psychophysiological capabilities of man, in the process of his interaction with technology, and the patterns of functioning of the man-machine system. Research within the frame of reference of engineering psychology is directed toward definition of the role of man in automated systems, and the creation of optimum control systems including people and automatic machines, and insuring the maximum effectiveness of control, taking account of the limitations imposed by the capabilities of technology and man. Engineering psychology solves problems of guaranteeing the transmission to the operator of all information, necessary for making timely /8
"operational" and "strategic" decisions, in the most suitable form for perception by the operator, develops algorithms[1] for processing information by a man, as well as the efficiency of this

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[1] An exact instruction on accomplishment of certain systems of operations, in a specified order, for solution of all problems of a given type, is understood by algorithm.

* Numbers in the margin indicate pagination in the foreign text.

process, taking account of permissible loads on the operator and the optimum division of labor between operator and machines and between operators (in systems which are attended by a team of operators).

In the long run, scientifically based recommendations are expected from engineering psychology, insuring the creation of the most favorable working conditions for operators in accomplishment of functional tasks facing a system, freeing operators from fatiguing, monotonous, stereotyped and repetitive actions, as well as solving creative problems.

As professor B. F. Lomov [59, 20], one of the leading specialists in the field of engineering psychology, correctly notes, the premises of this science were formed during the course of development of not only the psychological, but the engineering, sciences.

As an engineering science, engineering psychology studies control systems, but only from a specific point of view, elucidating what requirements are set forth by the construction of elements and the entire control system on the psychophysiological characteristics of the operator.

As a psychological science, it studies the psychophysiological processes and characteristics of an operator, but also only from a specific point of view, elucidating what requirements on control systems and their elements flow from the nature of these processes and characteristics.

The connection between psychology and the engineering sciences is mutual. On the one hand, psychological theory tests new machines during design and operation. On the other hand, the study of psychic phenomena discloses new capabilities for the solution of various engineering problems.

Sometimes, engineering psychology is considered only as a /9
science "of the capabilities and actions of a man working in control systems." This comparatively narrow understanding of the object and task of engineering psychology is scarcely justified, especially during its formative period.

In engineering psychology, man is not studied separately as a biological creature (this is the task of the anthropological sciences), automatic systems are not studied in themselves (this is a purely engineering task), but a unified operator-machine system, in which the guiding "element" remains man, with his natural capabilities of perception, calculation, information processing, application of a controlling action, etc., is analyzed and synthesized. Professor V. P. Zinchenko and G. L. Smolyan

[39] properly emphasize that the "engineering and human aspects of it (engineering psychology) are inseparable, and this is the practical value of engineering psychology."

Specialists in engineering psychology can be of the greatest use when they are included in a group of system planners, and do not " save " themselves for critical remarks on an already produced system.

There are at least three main directions in which specialists in engineering psychology carry on development of a control system:

distribution of functions between the operator and the machine (and between operators);

optimization of the man-machine system, according to selected criteria (adaptation of elements of the system to the operator and "adjustment" of the operator to the accomplishment of his functional tasks in the system);

evaluation of man-machine systems.

The study of"components" - operators and machines - differing qualitatively but functioning in a unified system, from a certain general point of view, became possible only as the result of the development of cybernetics.

It is now becoming completely right to distinguish engineering psychology in aviation and astronautics as a separate part or branch of engineering psychology.

The man-machine system functions under special conditions in aviation and astronautics: extreme conditions, which are not encountered in a normal ground situation, frequently accompany a man in flight in an aircraft. They are caused by various factors, which can be divided into three large groups: /10

the physical factors of space (barometric pressure, gas composition, characteristics of temperature regimes, various types of ionizing and nonionizing radiation, and others);

factors determined by flight dynamics (g- forces, weightlessness, noise, vibrations, high relative speeds, and others);

factors caused by staying in closed, relatively small spaces (isolation, duration of stay, relatively restricted motor activity, features of the microclimate and others), the effects of which increase unusually during a prolonged stay in this space.

A condition of stress on the operator, as a rule, accompanies extreme flight conditions. Man-machine systems for these conditions

must count on precisely this condition. The operator in an aircraft emerges, not only and not so much, in the role of "observer," as in the role of "controller," using a set of instruments, in which information on the state of a controllable aircraft and its systems is "included," for solution of control problems.

The conditions for selection of operators for flight, extent, duration and cost of their training are sharply distinguished from selection and training of "ground" specialists.

Engineering psychology in aviation and astronautics also can be considered a separate branch of engineering psychology, because the operator (particularly in spacecraft) can emerge, not only as a link in information reception and processing, generation of a decision and application of a control action, but as an object of control. He fulfills this function upon entering into open space.

The main tasks of engineering psychology in aviation and astronautics, applicable to conditions of atmospheric and space flight, consist of:

Study of the general efficiency of the operator's body and his psychophysiological characteristics in control of an aircraft and its systems under changing modes and conditions of flight, including the study of the functioning and interactions of the analyzers; /11

Substantiating medical-engineering requirements for systems of coding information coming to the operator, for the structure of parameters displayed, for organization of the control circuit, for the design of control devices and work places, for the purpose of bringing their characteristics into harmony with the psychophysiological capabilities of the operator;

Development of requirements for means and methods of selection and purposeful training of operators for schooling in control of aircraft (AC) and their systems, by means of formation of skills appropriate to the characteristics of control systems.

Special attention must be given, in solution of these problems, to clarifying the differences in principle between the functional characteristics of the operator in flight and on the earth (this is determined by the circumstance that training of operators for professional activities up to now has taken place on earth), as well as to determination of changes in functional characteristics of the operator during prolonged flight, since a short period under flight conditions can give characteristics (due to human reserves), which cannot be extrapolated to a more prolonged time.

Solution of the problems of engineering psychology in aviation and astronautics, in the long run, is directed, not so much towards increase in flight reliability and safety, as to increase in efficiency in use of the aircraft and its numerous systems. Experience and the results of research show that, without guaranteeing congruence of the aircraft control system characteristics and the psychophysiological capabilities of a man, manifested in operation of a complex system, the operator in an aircraft cannot successfully cope with the tasks placed on him in flight.

It must be noted that, in a number of cases, of necessity, /12 engineering psychology in aviation and astronautics is not succeeding in using the results obtained during research in engineering psychology. This is explained by the fact that, at present, the basic methods of research in engineering psychology are concrete experimental investigations of systems with operator participation. The output characteristics of the system and the characteristics of the operator in control are determined to a great extent by the parameters of these systems and the conditions under which the operator carries out his functions. Very frequently, neither is similar to those which will occur in aircraft during atmospheric and space flights. Therefore, experimental engineering-psychological research must be carried out again for these conditions.

The fact must be pointed out that a set of factors, accompanying flight and having an effect on the operation of the operator-AC system, simultaneously act on the operator during his flights in AC. In a number of cases, success is not achieved in reconstructing this set of factors on earth, and the conduct of engineering-psychological research directly in flight, obviously, is accompanied by extremely great and, sometimes, altogether insuperable difficulties.

The necessity for further engineering-psychological research in aviation and astronautics is determined by the continous expansion and complication of tasks facing aircraft crews, the increase in volume of onboard automatic and instrumental equipment, with which the operator must interact in flight, and a reduction in the functional capabilities of a man, owing to the increase in flight speed, the amount of overloads, the duration of action of other unfavorable flight factors, deterioration of the operating conditions of the operator (the presence of movement-constraining protective equipment, the unusual nature of functional tasks and others).

Civil aviation now is one of the leading types of passenger and freight transportation. It is becoming an all-weather type of transportation. Safety and regularity of civil aviation aircraft flights are increasing every year. The time is not far off

when supersonic liners, with their specific, inherent character of flight, will fly the Aeroflot lines. The projected trend in development of civil aviation permits the completely obvious conclusion to be drawn as to the increase in the role and importance of man in aircraft flight security, on the necessity for deeper and more extensive research in the field of engineering psychology, for creation of optimum man-machine systems in aviation. /13

And, whatever direction in development of aviation we examine, it is possible to affirm everywhere, with complete justification, that the conditions of crew operation will become more complex, the role and importance of mutual "adjustment" of man and technology in aircraft will undoubtably increase. Engineering-psychological research will absolutely assist in guaranteeing effective functioning of man in spacecraft (SC).

For safety of space flights, according to various programs, a number of complicated questions must be answered, in particular, these:

Is it necessary that man himself take part in the flight, or must he only control the flight of an automatic craft from earth? Can man operate effectively and usefully in flight? For accomplishment of what tasks is man most fitted? Where is the boundary between the use of automatically operating equipment and that controlled by man?

The well-known successes achieved in recent years in development of automatic aircraft control systems, the introduction into aviation of automatic data collection and processing devices, based on electronic machines, on the one hand, and the complication of aircraft and their systems and the expansion of tasks which can be solved by the crew under extreme flight conditions, with the limited nature of operator capabilities, on the other hand, have led a number of specialists to the conclusion that man is not necessary in an aircraft, that "man has ceased to be the absolute master in an airplane" [14], that the self-organizing, self-adjusting and self-repairing automatic systems solve any problems in atmospheric and space flight better than man [75].

There was a certain basis for pessimistic conclusions by specialists, with respect to the prospects for development of piloted aircraft. It is known, for example, that the number of aircraft accidents and disasters in the USA, due to the so-called "human factor," is from 30 to 70% of the total number of disasters and accidents (from data of various authors). When supersonic aircraft first appeared, the number of accidents also increased sharply. This is partially explained by the fact that, during flights at /14

speeds close to 3 M[2], optical illusions arose in the pilot: he saw objects abreast of the aircraft, which actually already were 100 m behind [29].

The unusual nature of conditions of space flight and inadequate knowledge of outer space has compelled the thought that man in a spaceship will be in trouble in solving certain problems. All this, it seemed, "confirmed" the necessity for a change from piloted to unpiloted aviation and to the development of automation of control of spacecraft.

However, nevertheless, the operator, by right, occupies and will occupy the central position in the complex AC control system. His logical capability, high selectivity and creative thought, all things considered, become the decisive factors in the entire system. No matter how well designed, how high the flexibility and efficiency of electronic computers (EC) and other data processing devices, only man possesses the gift of forecasting events on the basis of analysis, the capacity for making decisions and planning actions under conditions of a sudden shortage of information, a constantly and arbitrarily changing situation, which is especially characteristic of operating conditions in an AC.

In many cases, the operator and the automatic machines in an AC can carry out individual flight control operations with identical success. Tasks which are too difficult for the operator must, of course, be turned over to automatic machines (continuous and monotonous actions, stabilization in prolonged flight, routine navigation calculations, actions requiring rapid reaction and other things). There are a number of operations which only the operators can successfully carry out, and no automatic machine at all can be substituted up to now (evaluation of unforeseen situations, making final decisions, selecting landing sites and other things). Maximum automation is not always useful or suitable, both from the point of view of efficiency and of economy and reliability of AC control systems. /15

Thus, man and machine should not be opposed in analysis of AC control systems, but, in creation of these systems, the optimum combination must be made of the psychophysiological capabilities of the operator, having natural limitations, and the ever-increasing capabilities of automatic devices.

Here, to the point, it should be noted that even the use of aircraft not having operators aboard, completely automatically

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[2] M = V/a is the ratio of the flight speed to the speed of propagation of sound.

controllable, the necessity for solving problems facing engineering psychology in aviation and astronautics is not at all eliminated. The problems are only somewhat modified, since, in this case, the operators, located at ground control points, are connected with the objects which they can control remotely, and not directly.

Engineering psychology in aviation and astronautics is attracting the attention of workers in various specialties, from mathematicians, psychologists and designers to engineer-researchers, operators and pilots. They all make their contribution to research on the man-machine system, applicable to the ever more complicated conditions of flight and the ever-expanding tasks to be solved by crews in flight.

CHAPTER I. THE BIOMECHANICAL OPERATOR-AIRCRAFT SYSTEM AND OPERATOR FUNCTIONS /16

A piloted aircraft is a complex biomechanical system, the technical links of which function with participation of the operator.

By a complex biomechanical control system, we should understand that set of multicircuit and multichannel (in the general case, closed) systems, which include the operator (operators) and the machine and which are characterized by a diversity of sources of information and control devices, usable by the operator in the control process.

Let us examine the features of aircraft flight control and certain onboard systems, in the operation of which the operator (pilot, astronaut) takes part to one degree or another.

In the first approximation, the flight of an aircraft in an air medium can be considered as movement of a solid body, possessing six degrees of freedom. Actually, an aircraft in the air can turn in any direction around its center of gravity (center of mass), and the center of gravity can also be progressively displaced in any direction. Expedient use of an aircraft requires that its movement be controllable. Controllable movement of an aircraft in space, characterized by specific parameters in assigned coordinates (angles, velocities, accelerations), and intended for specific purposes, is called the flight mode. A given mode is maintained by change in parameters defining this mode, i.e., by purposeful change in the aircraft position coordinates.

Aircraft control systems have four main devices and a number /17
of auxiliary ones. The main devices are: the elevator, for providing longitudinal controllability, i.e., for upward and downward deflection of the aircraft from the direction of flight; the rudder, for providing directional controllability, i.e., for turning the aircraft to the left or to the right of the flight direction; the roll control surface (ailerons), for providing lateral controllability of the aircraft, i.e., for tilting the aircraft to the right or the left side; throttle lever, for control of engine thrust, and, through it, flight speed.

Auxiliary controls are: devices for regulating the force on control levers (trim tabs) and for deflecting panels or flaps, levers regulating operation of separate engine systems and operation and adjustment of various automatic machines, equipment, etc. Subsequently, we shall speak only of the main control devices.

Control systems consist of flying controls, located in the cockpit, control surfaces and electric wiring, connected with the

flying controls and the corresponding control surfaces. The flying control controlling the ailerons and elevators is called the control stick (in light planes) or control column (in heavy aircraft). Control of the rudder is accomplished with foot pedals, and control of the engine, by the throttle lever. From the point of view of the features of the work of the pilot as operator in decisions on various tasks of the flight program, the control system on an aircraft can be divided into two:

System of control of the aircraft position relative to the surface of the earth (flying system);

System of control of the aircraft position during flight along a planned flight path.[1]

The tasks of piloting an aircraft are the conscious maintenance or change in position of the aircraft in space relative to the surface of the earth, with simultaneous maintenance of flight safety conditions. The pilot resolves this task at all stages of any flight. /18

Control of the flight along a planned flight path is a more complex task for the pilot than control of the flight relative to the surface of the earth. Here, besides decisions on piloting tasks, the pilot must also make decisions on the task of stabilization of the center of gravity of the aircraft relative to the given flight path. The pilot makes decisions on these tasks in executing flights along flight paths assigned from earth or calculated onboard (for example, in landing, homing on aerial and ground targets, during formation flights and others).

Let us examine both of the control systems mentioned.

System of Control of Aircraft Position Relative to the Surface of the Earth (Flying System)

The movement of a flying aircraft can be considered as a displacement along a three-axis coordinate system, connected with the airplane, longitudinal (x-x) and two lateral (y-y) and (z-z), and rotation relative to these axes (Fig. 1.1). In the majority of cases, the group of longitudinal and lateral motions can be considered separately.

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[1] Of course there are other systems in AC, functioning with operator participation: electric power system, life support system; however, they are not examined in detail here.

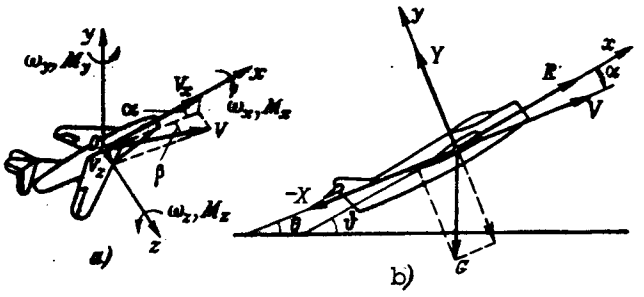

Fig. 1.1. Standard coordinate system connected with an aircraft (a), forces acting on an aircraft in flight, and coordinates defining the position of the aircraft with respect to the surface of the earth (b): xyz - coordinate axes; M_x, M_y, M_z - resultant aerodynamic force moments about xyz axes; ω_x, ω_y, ω_z - angular rate of rotation of the aircraft around the xyz axes; β - slip angle; θ - flight path angle, angular position of velocity vector in the vertical plane; ϑ - pitch angle or angular position of longitudinal axis of aircraft; $\alpha = \vartheta - \theta$ - angle of attack (on condition that the longitudinal axis coincides with the mean aerodynamic chord of the wing); R - engine thrust (it is assumed that it is applied to the center of gravity, coincides with the longitudinal axis and is a function of air density ρ and flight M number); X - drag (directed against the velocity vector and equal to $c_x S\rho V^2/2$); Y - lift (equal to $c_y S(\rho V^2/2)$); $G = mg$ - aircraft weight; ρ - air density; $\rho V^2/2$ - velocity head; S - wing area; $c_x = c_x(\alpha, M)$ - is the coefficient of force X; $c_y = c_y(\alpha, M)$ - coefficient of force Y; (coefficients $c_y c_x$ are given by the aircraft drag polars for different M numbers).

The elevator and throttle are used as the controls of the longitudinal movement group. The angular coordinates, defining the position of the aircraft with respect to the surface of the earth, are:

Flight path angle (θ) or angular position of the aircraft velocity vector with respect to the horizon;

Pitch angle (ϑ) or position angle of the longitudinal x-x axis with respect to the horizon;

Angle of attack ($\alpha = \vartheta - \theta$), i.e., the angle between the longitudinal x-x axis and the flight direction or velocity vector;

Engine thrust (R), which is a nonlinear function of air density, speed and magnitude of the control action (throttle position).

For a number of reasons, a rather distinct "set" of measurement parameters are used for monitoring and control of longitudinal movement in an aircraft, namely, bank-and-pitch indicator as the pitch and roll angle indicator; flight speed indicator, altimeter, rate-of-climb indicator (rate of change in flight altitude indicator) and angle of attack indicator (for the most part when landing). A block diagram of the process of control of longitudinal movement of an aircraft in horizontal flight is presented in Fig. 2.1. /19

Deflection of the control stick by the pilot and the movement of the elevator (δ_e) connected with it causes a change in the angle of attack ($\Delta\alpha$). The connection between δ_e and $\Delta\alpha$ is described by the transfer function of the oscillating link. Change in the angle of attack leads to the appearance of an angular velocity of rotation of the aircraft, and so, to change in the flight path angle $\Delta\theta$. The connection between $\Delta\theta$ and $\Delta\alpha$ is expressed by the transfer function of the integrating element, the time constant of which is proportional to the load per square meter of wing and inversely proportional to the flight speed. A change in θ causes the appearance or change in the vertical velocity $\Delta\dot{H}$ and change in the flight altitude ΔH. The values ΔH and $\Delta\theta$ are connected by the transfer function of the integrating element. /20

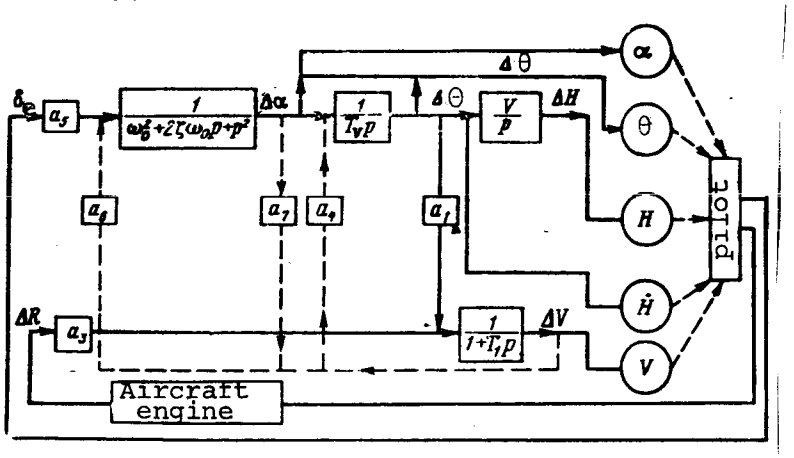

Fig. 2.1. Block diagram of control of longitudinal movement of aircraft.

The slip angle ($\Delta\theta = \Delta\alpha + \Delta\theta$), the altitude and rate of change in altitude are determined by the pilot by visual instruments. Change in aircraft speed ΔV is caused (after displacement of the throttle) by change in engine thrust ΔR, flight path angle and angle of attack. The connection of ΔV with ΔR, $\Delta\theta$ and $\Delta\alpha$ is characterized by the transfer function of an integrating element with a large time constant T_1, proportional to the speed V and inversely proportional to the thrust-weight ratio (the ratio of the thrust to the aircraft weight). A change in speed, in turn, affects the angular movement of the aircraft. This effect is shown by dashed lines in the diagram. The connections are weak and they cause the so-called long-period phugoid oscillations of the aircraft. Under flight conditions, control of the speed is accomplished by the pilot by coordinated action of two controls, the throttle and control stick, deflecting the elevator. In reaction to the engine thrust, the pilot first notices a change in flight speed and then a change in the flight path angle. /21

The pilot, in controlling the aircraft, pays attention to just the initial reaction of the aircraft to the control action and not the final one. Therefore, wishing to change the flight speed, he always acts on the engine thrust and he executes a change in the flight path angle by the elevator. These pilot actions are

contradicted by the requirements, flowing from the statics equations, in accordance with which the flight speed depends on the lift coefficient, i.e., deflection angle of the elevator, and the flight path angle, on the engine thrust value. The contradiction is removed, thanks to the coordinated action of both controls, which an experienced pilot executes by reflex action. Wishing, for example, to increase the flight speed without change in flight path angle, the pilot increases the engine thrust (gives gas). Noting the necessary increase in flight speed, the pilot prevents an increase in the flight path angle by an elevator reversal, thereby providing the necessary lift coefficient value for the new flight speed.

The pilot accomplishes a change in the flight path angle by operating the elevator. Noting the necessary change in the flight path angle, the pilot prevents a change in flight speed by action on the engine thrust. The additional change in the flight path angle arising in this case is countered by an opposite elevator reversal.

As a result of these manipulations, the aircraft flies at the former speed, but with a different flight path angle [22, 24].

Control of the aircraft lateral movement group, a block diagram of which (in the horizontal flight mode) is presented in Fig. 3.1, is executed by means of the ailerons and roll control surface. The coordinates of the lateral movement group control process are lateral roll (γ), heading (ψ), slip angle (β), angular velocity of the aircraft in the horizontal plane ($\dot{\psi}$), and linear deflection Δz of the center of gravity from the flight path. These parameters are measured by the appropriate measuring instruments. In the process of control, a close interconnection is found between the course and lateral movements of the aircraft (roll, yaw, and slip movements), caused by spiral moments, with coefficients K_{yp} and K_{xq}, as well as the effect of slip, represented by the coefficients $K_{x\beta}$ and $K_{y\beta}$. In fact, if the aircraft, for some reason or other, for example, due to a wind gust, turns to a certain angle relative to the incoming flow and begins to slip, the lift on the left and right wings turns out to be unequal, as a result of which a moment arises which banks the aircraft. On the other hand, if the aircraft banks, a centripetal force arises, curving the flight path. In this case, the incoming flow, acting on the vertical tail, causes the aircraft to turn. /22

The lateral force coefficient Z_β is small, and the time constant mv/Z_β (especially at high flight speeds) is so large that the link with the output value $\Delta\theta_g$ (the angular deflection of the velocity vector in the lateral plane) is practically an integrating element. In this manner, with unchanged precision in maintaining ψ and γ, the angular deflections in flight /23

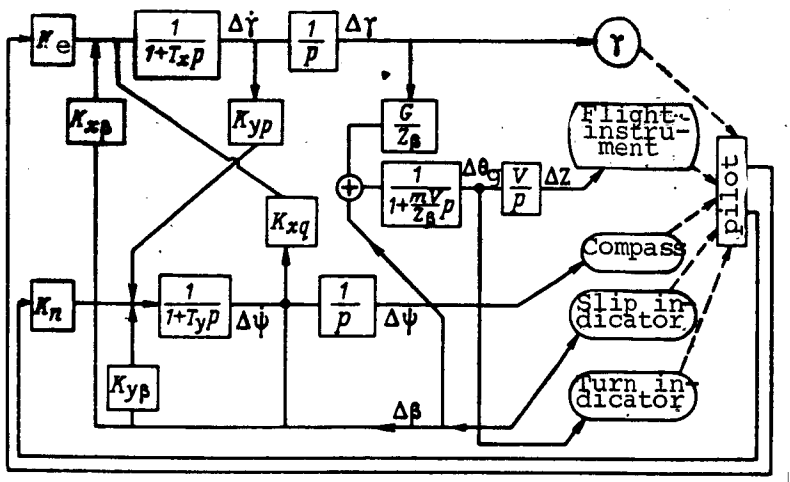

Fig. 3.1. Structural diagram of aircraft lateral movement group control.

direction $\Delta\theta_g$ decrease with increase in speed, and the linear deflections ΔZ remain unchanged. The interconnection between the course and lateral movements of the aircraft predetermine the necessity for coordinated action with the aileron control surfaces and the rudder, which requires the development of stable control skills by the pilot.

Taking this into account, and keeping in mind as well that, in control of the lateral movement group, not one,but several, control instruments must be used, ample difficulty can be noted (from the point of view of the psychophysiological characteristics of the operator) in executing the task of aircraft control.

By action on the controls (in control of longitudinal and lateral movement), the parameters defining stability, controllability and safety of an aircraft, as well as parameters, having a harmful effect on the human body, can change beyond permissible limits.

Among them are:

velocity head, the minimum value of which is limited by the lift necessary for accomplishing flight, and the maximum, by the strength characteristics of elements of the aircraft structure;

M number, at specific values of which the stability and controllability of the aircraft deteriorate sharply;

pressure drop in a hermetically sealed cabin;

G-force, the maximum value of which is limited by the physiological characteristics of man and the strength characteristics of the aircraft;

aircraft slip;

fuel supply, determining the possibility of successful completion of a flight mission.

The necessity for monitoring the parameters indicated leads to complication of the task of the operator in aircraft control.

System of Control of Aircraft Position During Flight on a Planned Course

The task of stabilization of an aircraft center of gravity on a strict space flight path is considerably more difficult for the pilot than the task of stabilization of the angular position of the aircraft relative to the surface of the earth. The pilot must execute flight on an assigned flight path essentially at all stages, at takeoff, en route, in homing on aerial and ground targets, in landing approach and during landing. On the basis of information coming from different flight instruments, the pilot must quickly make a decision on the nature and degree of action on the controls, in order to stabilize the aircraft on the flight path. /24

The complexity of aircraft control during flight on a planned course consists of the fact that, in the course of the flight, by action on one control surface or another of the aircraft, the readings change on not one, but as a rule, on several monitoring and control instruments at once, since the group of parameters monitored by these instruments is interconnected through the object of control (the aircraft). And the task of the pilot, "moving the aircraft forward" along a flight path, consists of reducing the interdependent readings of the instruments included in the control circuit to fully specified values.

It should be noted that, during flight of an aircraft along an assigned flight path, the pilot executes two sets of tasks: he controls the angular coordinates of the aircraft and the position of the center of mass of the aircraft relative to the flight path.

During flight along a planned flight path, the pilot particularly frequently has to distribute his attention among several instruments or several groups of instruments and simultaneously execute a series of actions.

Research on the higher nervous activities has established that, if a man executes several actions, one of them may become dominant. In this case, his main attention is concentrated on it and the man is diverted from executing the other actions.

In flight practice, this phenomenon can be observed quite frequently, when, upon deviation of the aircraft from the planned flight path, perception of the readings of one instrument or another becomes dominant in some pilots and, simultaneously, they do not note changes in the readings of other instruments. Knowing

of this peculiarity, each pilot must, by a conscious effort of will, direct his attention to execution of all necessary actions, even if they appear to be nondominant at a specific moment.

Let us dwell on certain features of the controllability of /25
modern aircraft, which affect the accomplishment of aircraft control tasks by the operator, and which must be taken into account in development of control systems and training of pilots.

By controllability of an aircraft, we understand its capacity for changing its position in space and, consequently, flight mode by deflection of the control surfaces.

Aircraft controllability is characterized, first, by the magnitude of effort which must be applied to the controls for a change in the flight mode and, second, the speed of transition from one mode to another, which is particularly important in executing sudden maneuvers in precision flying (upon landing, during formation flight, etc.). From the point of view of flight safety, it is necessary that entry of an aircraft into dangerous modes (according to structural strength or controllability) not take place unexpectedly for the pilot. Therefore, it is desirable that the effort required for changing the aircraft to limiting modes be distinctly felt by the pilot or even exceed his physical capabilities.

Controllability, like stability, usually is analyzed separately for each axis. Longitudinal controllability is determined by the capacity of the aircraft to rotate around the transverse z-z axis during deflection of the elevator; directional control by the capacity of the aircraft for rotating relative to the normal y-y axis during deflection of the rudder; and, finally, lateral controllability, by the capacity of the aircraft to rotate relative to the longitudinal x-x axis during deflection of the ailerons.

All types of controllability depend on the control surface areas, flight speed and altitude, length of the tail section of the aircraft and weight distribution along the length of the fuselage and on the wing spread (moments of inertia).

There is a mutual connection between directional and lateral controllability, consisting of the fact that a turn causes a bank and a bank causes a turn.

The effort to improve the stability and controllability characteristics by aerodynamic means is not the optimum solution of the problem in all cases, since even considerable structural changes do not always give the desired results. In particular, even doubling the area of the vertical tail of one type of air- /26
craft, for an increase in directional stability and controllability,

leadsto a decrease of only 50% in the amplitude of vibration of the aircraft during lateral movement. However, this increase in area of the vertical tail, in turn, leads to an increase in the susceptibility of the aircraft to wind gusts, an increase in drag and making the structure of the aircraft heavier, which entails additional complex problems. This is evidence that it is practically impossible to give an aircraft the desired controllability characteristics in all flight modes, with the aid of aerodynamic means alone.

Improvement in these characteristics can be achieved by way of inclusion in the control system of a special automatic device, a so-called pitch damper, giving control signals for deflection of the elevator without the pilot's knowledge, depending on the angular velocities around the z-z axis.

The presence of high lateral stability is inherent in swept wing supersonic aircraft, but, due to negligible damping of these aircraft, vibrational instability in lateral movement of the aircraft appears around the normal axis, the so-called "Dutch roll." For prevention of vibrational instability, the pilot must deflect the rudder and ailerons in proportion to the rate of change in the bank and yaw angles, due to which, manual control of the aircraft is very strongly hampered. And here again, installation of a special yaw damper is necessary.

Controllability of an aircraft is determined by its structure, but the structure already is a constant factor in a planned aircraft. Therefore, for an aircraft of any construction, the effect of changing flight conditions, speed, altitude, air density, naturally will show up in controllability. With a decrease in flight speed, in approximate proportion to this decrease, the time for transition of the aircraft to the new assigned flight mode, after deflection of the control surfaces, is increased. In modern aircraft, the time for transition to the new mode at low speed is 5-6 times greater than this time at maximum speed. The aircraft becomes "sluggish" in control at low speeds. With increase in flight altitude, the time for transition of the aircraft to a new assigned mode, upon deflection of the control surfaces, increases approximately the same number of times as the air density decreases. At an altitude of 20 km, its density is approximately 14 times less than at sea level. Controllability of the aircraft deteriorates sharply at high altitudes. An aircraft with normal controllability, to which the pilot is accustomed, has a damping of the short-period vibrations in establishment of a new angle of attack or G-force which is close to the optimum, $\sqrt{2}/2 \sim 0.7$, and a natural vibration frequency of 0.5-0.7 Hz, which corresponds to the duration of the transition processes of 1.5-2 sec. In modern, high-speed aircraft, the relative damping of the short-period vibrations is considerably decreased (with increase in speed

/27

and flight altitude), and it amounts to 0.05-0.4 sec, and the transition processes in angle of attack and angular pitch frequency have a clearly expressed oscillatory nature, and it terminates, depending on the flight mode, in 8-15 sec. Such an aircraft reaction to control actions by the pilot is unsatisfactory.

Concerning the slow, undamped oscillations in speed, altitude and angle of pitch of the aircraft about their established values (the oscillation period is on the order of 1 min and more), the so-called phugoid oscillations, they do not cause any difficulty to the pilot, who knows of the balance characteristics of the aircraft, as a function of the flight speed and altitude.

At high altitudes, a supersonic aircraft has a considerable lag in establishment of the angular rate of bank, and this, in turn, leads to difficulty in control of the angle of bank. Owing to the inadequacy of damping around the longitudinal axis, establishment of a specific bank takes place with considerable oscillations, which terminate, depending on the mode, in a time of up to 15 sec, while the value of this quantity to which the pilot is accustomed is 1.5-2 sec. Thus, this circumstance obliges the use of special automatic means (roll dampers) in the manual roll control channel.

The compressibility of air causes considerable displacement of the aerodynamic center of the wing, as a result of which the generation of large diving or pitching moments can take place. In this case, the effort on the lever, necessary for the deflection of the control surface, created by the moment, counteracting the moments indicated above, becomes too great for the pilot, and the aircraft can go out of control. Special automatic means also are necessary here. They must assist the pilot in control of the aircraft during aircraft instability as to angle of attack, as a consequence of the location of the center ahead of the center of gravity.

Supersonic aircraft become unstable in flight speed, owing to a more precipitous increase in available thrust than is required at high flight speeds.

With increase in flight M number, the effectiveness of the ailerons drops, which leads to a decrease in the gain of the aircraft as an object of control. In order for the pilot to have the same feeling of lateral controllability at all flight speeds and altitudes, it is evident that the introduction of a special automatic device is necessary, the parameters of which would change with change in flight speed and M number. It is typical of supersonic aircraft that, with deflection of the control stick and a large change in the angle of attack in this case, the aircraft flight path changes insignificantly, which can disorient the pilot

in flight, especially, if this phenomenon is accompanied by a slow damping of the aircraft oscillations. Here also, introduction of an appropriate automatic device into the control system is necessary.

As has already been pointed out, aircraft flight speed control is now accomplished, not directly, but through engine thrust. The pilot, operating the throttle, changes the engine thrust. After the change in thrust, the flight speed begins to change, until the time when the drag at the new speed balances the new thrust value. In this case, the pilot cannot tell precisely beforehand what speed will be established after he moves the throttle. Therefore, the process of establishing speed is long and requires several actions on the throttle. This is extremely fatiguing, in precise maintenance of speed during landing, and especially, during aircraft formation flight, if it also is considered that the change in flight speed by operating the throttle very definitely depends on the flight altitude. Moreover, this flight speed control information leads to considerable fuel overconsumption of the aircraft piloted. The process of speed control also requires automation. /29

During flight at high speeds, the effort on the flight controls may reach such values that, to reduce them by normal methods of aerodynamic compensation does not appear possible. Therefore, boosters are used in control systems on modern, high-speed aircraft, the operation of which is based on the substitution of fluid pressure for the effort of the pilot.

Thus, the basic tasks in aircraft control are composed of:

Stabilization of the angular position coordinates of the aircraft axes relative to the surface of the earth (stabilization of the bank, pitch and yaw angles);

Stabilization of the true airspeed vector of the aircraft, i.e., stabilization of the flight path position and movement along the flight path (stabilization of speed, heading, angle of attack and flight altitude).

From what has been said of the mechanism of action of the moments and forces on an aircraft in the process of its control, it is clear that, for accomplishment of effective control of an aircraft by the pilot, a knowledge of the values and directions of the forces and moments is necessary, as well as of the angular coordinates of the aircraft during its rotation relative to the center of mass and the rates of change in them and the angular coordinates of the aircraft axes relative to a selected flight path and the rate of change in them.

In this manner, in controlling an aircraft, the pilot carries out predominantly tracking-regulation, i.e., maintains the value of a given parameter , as well as purposeful change in any parameter. Thus, for example, during the takeoff and landing run, he maintains a given direction, countering deviations arising by the control surfaces; in landing, he brings the aircraft to earth /30
along a specific flight path, matching his movement with the rate of descent; in horizontal flight, he maintains given altitudes, speed and heading, and in formation flight, distance, interval, elevation, etc. In many cases, a visual signal, or more precisely its change compared with the necessary or assigned value (mismatch), is the "command" for introduction of additional corrections.

In a number of cases, control by aircraft systems is accomplished by the pilot by commands coming through the audio analyzer.

Let us now examine the features of certain control systems of piloted spaceships.

The features of spaceship control systems and the nature of the work of an operator in these systems, naturally, depends to a great extent on the type of ship and its purpose.

During flight in a spaceship, an astronaut exercises control of orientation of the ship (change in pitch and yaw angles and rotation), as well as of its speed of movement, which leads to a change in orbit of the flight of the ship, in accordance with the laws of celestial mechanics. In this case, the ship control system can operate in the manual, semiautomatic or automatic modes. Jet engines usually are used as the system's final control elements.

Information necessary for control of orientation is obtained with the aid of optical devices, as well as of remote angle and angular velocity indicators, working together with vertical and heading sensors and with sensors of the angular velocity of the object. In manual control of the ship, a cosmonaut processes the data on angles and angular velocities, determines the magnitude of the control signals and makes the appropriate deflection of the control stick. The stick, through kinematic transmission, moves the jet engine working substance feed throttle of the manual control system. These engines create moments, proportional to the angles and angular velocities of the ship [23, 26, 32].

If the astronaut carries out orientation control by means of /31
dampers, he deflects the control stick in proportion to the angles. The signals of these deflections are transmitted to a computing device, where they are summed with the angular velocity signals. As a result of this, the moments created by the jet engines of the dampers also will be proportional to the angles and angular velocities.

Analysis of a spaceship orientation control system is a basis for considering that, on the whole, psychophysiologically, this system is much different from the stabilization system of a modern aircraft for the operator. These features and differences consist of the fact that indicators (optical orientors) are used, which are significantly different from known aircraft instruments (bank-and-pitch indicator and compass). The orientation system controls also have their structural individualities.

The work of an astronaut in orientation control proceeds under unusual conditions of complete dynamic weightlessness and hypodynamia, which accompany orbital flight. From the point of view of the dynamic characteristics, the ship orientation control system can be characterized fundamentally as a control system with slowly flowing processes, which puts the astronaut in unusual circumstances, which, in distinction from conditions of a rigid limit or deficit of time, can be called conditions of an "excess" of time. However, in approach and docking of spacecraft, during their deorbiting, descent and landing, time deficit conditions can arise.

With too slow an input of information and slow flowing of control processes (with a time "excess"), the operator begins to be distracted from monitoring the course of a given control process, which can lead to incorrect actions and to deterioration of the quality of control operations of the ship and its systems.

Prolonged holding of the control lever in the deflected position by the operator requires his concentrated attention on holding it in the necessary position. As a result of hand fatigue and dulling of the attention, involuntary switch off and erroneous /32
switch on of control channels, needless expenditure of reaction mass, deterioration of the accuracy of orientation takes place, and monitoring of the instrument data and signal indicators, included in other control system, is hindered.

The system of semiautomatic approach and docking of ships in orbit is a multicircuit instrument tracking system. In it, the operator (or operators), from his ship, carries out remote control of the angular positions of the docking unit, rate of approach, relative distance and line of sight direction.

The time which is available to the operator during work on the final stage of approach amounts of several minutes. The tasks of the operator, under the unusual conditions of weightlessness, in approach of the ship and station, are new and exceedingly complex. They are more complex than the most difficult tasks of aircraft crews in flight in closed formation or in aerial refueling. The time deficit and operator overload with information coming from many control channels can cause abrupt shifts in his activity,

reducing the reliability of the work. Incoming signals can be missed and delayed reactions to the complicated situation can appear, during which these omissions of signals take place in logarithmic dependence on the rate of input of signals to the operator. Considering the exceptional emotional stress on the operator, due to the extreme responsibility of the task, the work of the operator in the approach and docking control system is highly complex and difficult, requiring mobilization of all his psychophysiological capabilities.

Control of the ship after its descent from orbit for landing is a complicated scientific-technical task, determined by the unsatisfactory dynamic characteristics of the descending craft and the action of quite high G-forces on the operator for prolonged times after his stay under weightless conditions. The main feature of this stage of flight of the ship is that descent of the ship, for example, during flight in the atmosphere of the earth, is possible only in a comparatively narrow corridor, the coordinates of which are determined by the permissible heating of the skin of the ship and the permissible values of braking overloads for the ship's structure and its crew. Besides, the descent must be, as a rule, not arbitrary, but must guarantee landing of the ship in a planned region. All of this leads to the necessity for accomplishing the descent of the ship and exercising control of it, not on an arbitrary flight path, but along a completely specified curve in space. And, in this control system, the operator must carry out, in addition to logical operatons, tracking functions, putting the required descent program into practice. /33

From the cybernetic point of view, all spaceship systems with operator participation, like all biomechanical systems in an aircraft, can be reduced to several types.

Standard Control Systems with Operator Participation in Aircraft

Control of a piloted aircraft (AC) is a particular case of control of a machine exercised by man.

The biomechanical man (operator)-machine system is a system in which the controlling part is man. In this system, the operation of the machine is provisionally represented by readings of an instrument (instruments) monitoring this operation. In order for the machine to properly carry out its function, the characteristics of its operation, as well as all changes in its operation must be very accurately and quickly reflected by the instrument. Further, the instrument readings are received by the sensory organs of the man.

Reception and perception of the instrument readings are the basis for stimulation of a response reaction by the man.

To guarantee effectiveness of this reaction, the incoming information from the instrument must be simple and easily assimilable.

The response of the man is the means with the aid of which some mechanical control system of the machine is operated. This control must be directly connected with the primary operation of the machine, so that the control manipulations directly show up in the operation of the machine, and the operation of the machine, in turn, must indirectly and accurately be reflected in a change in the instrument readings. These readings inform the operator whether or not it is necessary to add additional changes to the control. In practice, many functions of the primary mechanism are connected into an entity and are a complex system of instruments. A unit diagram of the pilot-aircraft or astronaut-spacecraft system is presented in Fig. 4.1. /34

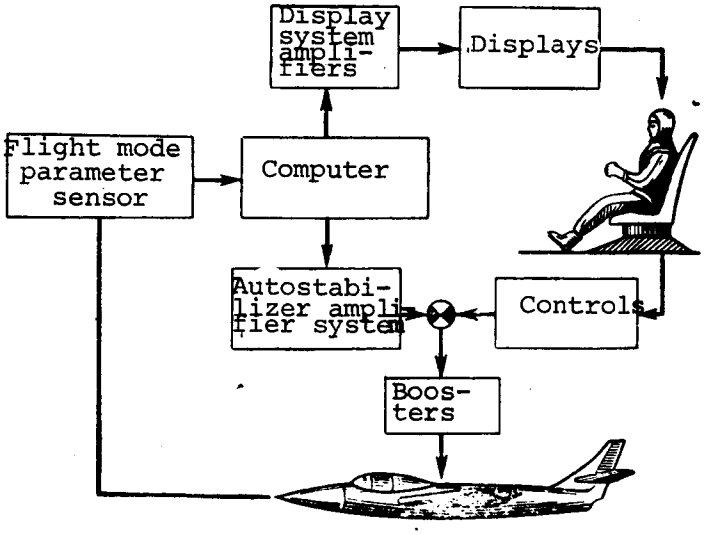

Fig. 4.1. Unit diagram of pilot-aircraft or astronaut-spacecraft system.

The operator in an AC, using one set of instruments and controls or another, establishes, maintains and changes the flight program.

The nature of the work of the operator in one control system or another varies and depends on many factors, in particular, on the dynamic properties of the object of control and all components of the system, control relationships realized in one system or another, methods of encoding information, the nature of the tasks facing the operator, external control conditions, structure and placement of controls and, finally, the psychophysiological capabilities of the operator [21, 22, 24]. /35

The activity of the operator himself, as the controlling element in closed astronaut-spacecraft or pilot-aircraft systems, can be characterized by the following three stages:

Obtaining and perceiving information from different instruments, signalling devices and the external medium (sensory functions of the operator);

Processing the information obtained and working out the necessary control actions for control of the AC and its systems, i.e., estimation of the accepted parameters of the controllable process, the surrounding medium (conditions) and disturbing influences, their correlation, interpretation and comparison with the parameters of the desired (or planned) control process and making a decision on the nature, magnitude and direction of the control action (calculation-logical functions of the operator);

Application of a control action to the controls of the AC and its systems or delivery of some control order (motor functions of the operator).

A diagram of the interrelationships of the actions and responses of the operator and the machine is given in Fig. 5.1. In examination of closed control systems with operator participation, it should not be forgotten that they remain as though open during the intervals between periods of monitoring of the flight parameters and applications of a control action. The deviations, proportional to the gain factors of the components, the length of the time interval and the values of the input quantities are accumulated at the integrating element outputs during these intervals of time. To guarantee proper accuracy of a control system with operator participation, fully specified monitoring periodicity must be selected. The monitoring periodicity must also be in concordance with the nature of the arbitrary change in the controllable parameter with time.

In the course of engineering-psychological research in development of control systems and their elements and in training of operators for professional activity, an evaluation of a control system with operator participation must be carried out. For working out a common approach to investigation of these systems, it seems advisable to reduce all of the diverse control systems in an AC to several standard systems, in which the basic elements, the operation of which must be evaluated in investigation of any system, would be separated out. /36

Standard semiautomatic (with operator participation) control systems in AC, being operator-AC systems, usually operate on the "tracking-pursuit" or "tracking-compensation" principles. Fig. 6.1 illustrates these two principles. Usually, they can be

distinguished by the indicating devices used. In the upper part of the figure, a "tracking-pursuit" system is shown, in which the operator sees the values of the system input and output signals. The task of the operator consists of reducing to a minimum the mismatch between the location of the target blip and the tracking pointer of the object controlled, in which both the blip and pointer are movable. In the lower part of the diagram, the compensating type tracking system is shown, in which the operator sees only the mismatch e(t) between the disturbing influence i(t) and the system output r(t). /37

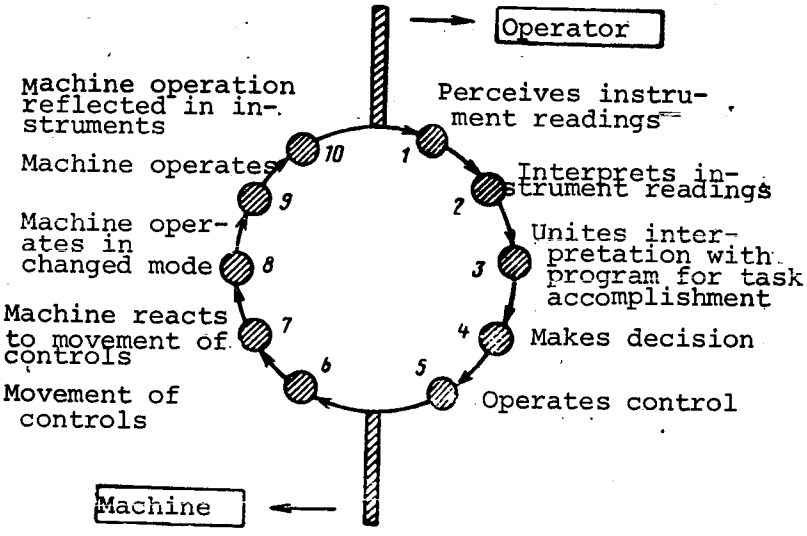

Fig. 5.1. Diagram of interrelationship of actions and responses of operator and machine.

As follows from flight practice, the operator carries out control functions with several AC systems in parallel.

The operator functions in a complex control system are reduced mainly to compensation tracking of many indicators, monitoring operations over the values of regulatable parameters of the object, mathematical and logical processing of incoming data from the instruments and signal indicators, correlation of the monitoring results and their comparison with the plan of action, selection of a decision for control of the object and putting this decision into practice through the controls, by means of applying the appropriate action to them.

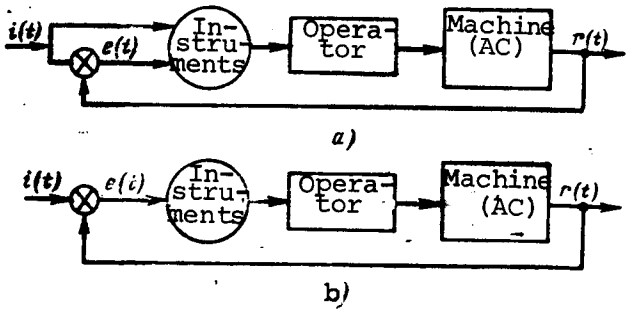

Fig. 6.1. Diagram of semiautomatic aircraft control systems: a. "Tracking-pursuit" system; b. Compensating type tracking system.

It should not be forgotten that, in developing an AC control system, at least two methods, connected with obtaining of information by the operator must be put into practice, namely:

The load relief method, in which the operator is freed from the necessity of carrying out complex logical operations in interpretation and calculation, owing to preliminary processing of data by means of computing devices; /38

The acceleration method, in which the operator obtains information immediately after action on the control levers of the AC or of its systems.

Since the purpose of both methods is the creation of conditions, in which the accomplishment of only those functions is required of the operator for which he is best fitted, these considerations are important in developing AC control systems.

Direct participation by a human operator in the operation of the numerous AC systems is ultimately directed towards resolving the basic flight task. The basic AC flight task, with participation of a crew carrying out control operations of an AC and its systems, is putting the assigned flight program into practice.

Accomplishing a flight program is a set of AC crew actions, in selection and processing (correlation, interpretation, comparison with the flight plan) of various data coming into the operator through the analyzer system from the instruments, sights, gunsights, signal indicators, communication lines, from the space surrounding the AC, from other operators in the crew or at flight control points, as well as actions connected with generation of command controls and application of control actions to the AC and its systems [12, 22].

Astronaut-spacecraft and pilot-aircraft systems are complex systems for obtaining, transmission and processing of information, the shaping of control actions and decreasing the entropy of deviations from the desired process.

The operator in these systems has to carry out the roles of both one and several elements: the role of logical and computing

devices, measurer of the control process parameters, amplifier, integrating or differentiating elements, devices for shaping control actions, as well as other types of feedback and the role of information source for other operators.

It should be noted that accomplishment of these functions of /39
control of an AC and its systems is accompanied with great difficulties for the operator, caused by the unusual conditions of flight, which are particularly manifested during spacecraft flight.

The following are factors affecting the functional capabilities of an astronaut:

change of the gravitational field within wide limits; transition from high G-forces to partial, and then, to total weightlessness, as well as the reverse transition from weightlessness to considerable G-forces;

prolonged stay under weightless conditions;

prolonged hypodynamia and the specific cabin microclimate;

isolation, limited influx of external sensory stimuli, loss of contact with the accustomed social life on earth;

emotional stress.

As some investigators think, the intensity of the emotional stress on a man increases at a faster rate than the force of motor responses, as is shown schematically in Fig. 7.1. Effectiveness of accomplishment of tasks of various degrees of complexity (difficult ones, moderately difficult ones, easy ones) depends on the increase in emotional stress [84]. A weak stress increases effectiveness and accomplishment of tasks of various degrees of complexity, but, above a certain optimum stress value, effectiveness is reduced progressively, and the greater, the more difficult the task. This relationship, first described by Gerks and Dodson, is presented in Fig. 8.1.

A complex object of control, such as a spacecraft, with its various sytems, and the unusual nature of the conditions of space flight, require, to a greater degree than in other AC, concordance between the characteristics of control system and the functional capabilities of the operator.

Study of the psychophysiological capabilities of an operator in an AC is composed of: investigation of the interactions of analyzers in flight, investigation of sensorimotor acts in accomplishing control, using information models, clarification of the principal differences between the functional characteristics

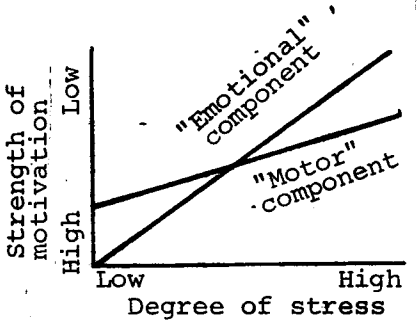

Fig. 7.1. Relation between stress and motivation.

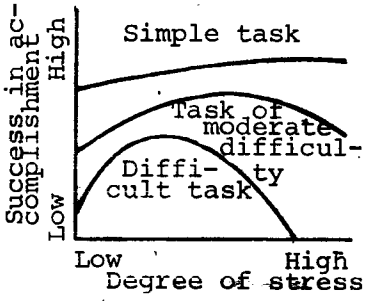

Fig. 8.1. Diagram illustrating the Gerks-Dodson principle.

of the operator under flight and ground conditions (since operator training is conducted initially mainly on the ground), determination of the functional characteristics of the operator in prolonged flight, since a short stay by him under flight conditions can give characteristics (because of reserves) which cannot be extended to a longer time. /40

From analysis of the foreign works in the field of optimum adjustment of man and machine (in the man-machine system), the survival of empirical aims in them are clearly seen. Despite the abundance of "methodological" reasoning, which, even in combined works, usually occupy an important place, a considerable part of the specific investigations appear to represent inadequately theoretically based searches for new quantitative determinations. A second tendency appears clearly here, to consider man only from the engineering point of view, only as one of the elements of an engineering system, not yet replaced by automatic devices.

However, the indication of inaccuracy of the approach which places the operator functions in an automated enterprise in a single series with the functions of the machines and which completely subordinates the first to the latter, in no way means that the operator generally cannot be considered from the point of view of his connections and interactions with the engineering devices. A conception of the man-machine system is not only justified, but progressive. It is precisely this concept which permitted setting up the problem of optimum adjustment of man and control apparatus. /41

Solution of the task of engineering psychology is complicated by the circumstance that it has to do with the study of the "characteristics" of man. The amount of data on the behavior of man during his operation with control apparatus is extremely limited, and these data prove to be quite inaccurate after extrapolation.

In order to build an effective AC control system, the characteristics of all components of it must be known, including the "characteristics" of the operator and his static and dynamic properties.

It is true that efforts to "pack" the psychophysiological activities of the operator into systems developed by the technical sciences, and to explain one feature of the work of the operator or another from the position of a functioning machine, should be guarded against.

The great amount of experimental data existing in the literature on determination of the transfer function of the operator, unfortunately, does not permit an optimistic conclusion to be drawn relative to whether or not determination of the transfer function of the operator makes it possible (in every case, at a given stage of research) to carry out calculations of a control system with operator participation, as is done for completely automated regulation systems. Further, evidently, the use of a more complex mathematical apparatus is necessary, taking account of the changeability of the reactions and functional characteristics of the operator, as functions of a diversity of different factors.

The fact is that, by virtue of the exceeding complexity of the psychophysiological processes taking place in the body of a man while he accomplishes a control action, the nature of which has been inadequately revealed up to now, and owing to a large number of factors having an effect on the psychophysiological capabilities of the operator, the transfer function of the operator cannot be expressed by any one relation, and it is impossible to determine any "normative" transfer function of an operator, which is standard for the majority of operators, under specified conditions of their activities. And it is precisely only these and, strictly speaking, not a broad, countless diversity of transfer functions, which could assist in solving the basic task, to substantiate and apply a strict mathematical approach to synthesis of a control system with operator participation. /42

Study of operator capabilities must be carried out on the basis of a sufficient amount of laboratory, test stand and flight experiments, with participation of a comparatively large number of operators, so that the characteristics revealed might be more generalized and not carry a significant imprint of the individual qualities of a pilot or astronaut.

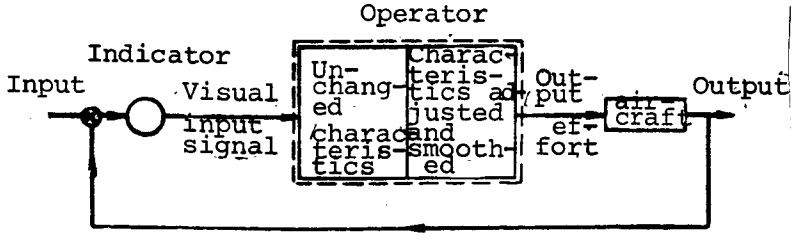

Fig. 9.1. Diagram of control system with operator participation.

On the basis of numerous observations and experiments, the operator characteristics in a control system can be divided into two basic component parts (Fig. 9.1): a) relatively unchanged and constant

characteristics and b) characteristics, changeable as functions of specific work. A number of schemes have been proposed by different investigators, representing the order of accomplishment of operator control actions. In one of the simplest ones, the operator is represented as an amplifying element, with a transfer function of the type

$$W_{\ell}(p)=K_{\ell}\frac{e^{-\tau_1 p}}{1+\tau_2 p},$$

where τ_1 is the time constant of the sensory reaction of the operator (equal to 0.25 sec on the average); τ_2 is the time constant, characterizing the inertia in formation of motor (effector) actions (equal to 0.125 sec on the average); K_{ℓ} is the gain; e is the natural logarithm base, 2.73...; and p is a Laplace transform. /43

It should be noted here that the rate at which an operator reacts to actuating information depends on many factors:

stimulus signal modality (the time for an auditory reaction usually is less than for light);

stimulus intensity (increase in intensity above the sensitivity threshold does not accelerate the reaction);

experience (for simple reactions, experience can reduce the reaction time by approximately 10%);

readiness (readiness to perceive a signal reduces the reaction time);

development of the motor capacities of human organs.

Moreover, the insensitivity band of analyzer systems of the operator should not be forgotten. In use of light stimuli, the insensitivity band is determined by the resolving power of the operator's vision, which amounts to approximately 1 angular minute. If the operator has to observe several instruments simultaneously, it is obvious that this is equivalent to an increase in the insensitivity band and reaction time.

In the scheme represented in Fig. 10.1., the operator is represented in the form of three series-connected functional "links." The first link, in which reception of measurement data from the instruments (or auditory information) and summation of the signals in specific proportions is carried out, according to dynamic properties, is an amplifying link with a delay. Its transfer

function $W_1(p)$ is

$$W_1(p) = e^{-pn\tau},$$

where n is the number of control instruments and τ is the time constant of the link.

The second link is a specific self-adjusting calculation unit. In this link, amplification and differentiation of the signals received is carried out. From the point of view of dynamics, this unit has the properties of amplifying, inertial (aperiodic) and boosting links. The inertia is due to the necessity for working out a decision as a result of correlation of the information obtained by the operator. The greater the volume of information and the less perfect the display system of the instruments used by the operator, the more inertial is the second functional link. The operator attempts to compensate for his inertia by way of generating booster, anticipatory signals. This is explained by the presence of a dynamic link with transfer function $T_\phi p + 1$. Therefore, the resulting transfer function of the second operator link will be /44

$$W_2(p) = K_0 \frac{T_\phi p + 1}{T_0 p + 1},$$

where K_0 is the operator gain factor; T_ϕ is the time constant of the booster link of the operator; and T_0 is the time constant of the inertial (aperiodic) link of the operator.

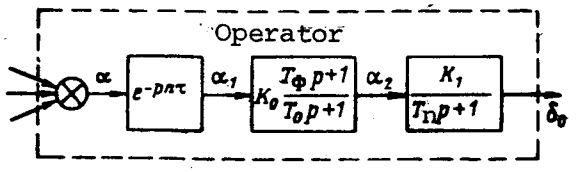

Fig. 10.1. Block diagram of operator transfer function.

With sufficient training, in the absence of disturbing influences and minimum psychophysiological stress, the operator is in a condition to form a booster link, which would compensate for the effect of inertia. In this case, $T_\phi = T_0$, and the second link is converted into a normal amplifying one, with the transfer function

$W_2(p) = K_0$.

The third operator "link" is the neuromuscular action on the object of control or a unique power amplifier, the input signal of which is α_2 and the output, the action on the AC control element. According to dynamic properties, this is an inertial /45

link, with transfer function

$$W_{\text{н}}(p)=\frac{K_1}{T_{\text{н}}p+1},$$

where K_1 is the gain factor of the neuromuscular system.

The time constant of the neuromuscular link $T_{\text{н}}$ depends on individual peculiarities, the psychophysiological condition of the operator and on the design and placement of the manual controls. It is considered that $T_{\text{н}}$ changes within the range of 0.1-1 sec, on the average. The total transfer function of an operator $W_{\text{оп}}(p)$ with sufficiently good professional training will be

$$W_{\text{оп}}(p)=e^{-p\tau}K_0\frac{K_1}{T_{\text{н}}p+1}.$$

In simplified form (at $T_{\text{н}} = 0$, $n = 1$ and $K_0K_1 = K$),

$$W_{\text{оп}}(p)\approx Ke^{-p\tau}.$$

This means that the operator accomplishes a K-fold amplification of the input signal with a time delay τ (on the average, τ changes within the limits of 0.2-0.5 sec).

There is a scheme, according to which the operator reaction to continuously incoming information is not continuous, but discrete. This, evidently, is connected with the fundamental principle of transmission of signals along human nerve fibers. It is known that this principle is briefly formulated thus: "all or nothing." In other words, the signal either is transmitted by the central nervous system or is not transmitted.

The central nervous system receives stimuli from the sensitive elements in the form of electrical signals, and, by means of feedback, carries out a comparison of these signals, held in the short-term (operative) memory. The time expended in this comparison is approximately 0.3 sec. This time is designated by the interval $0-T_1$ in Fig. 11.1. At moment $t = T_1$, a decision is generated to send an electrical control signal to the final control element. The final control element responds to the control signal received by a reaction in the form of a movement. This takes place in interval T_1-T_2, equal to 0.2 sec, in the course of which /46

the attention of the operator is completely devoted to monitoring the final control element action. The central nervous system does not receive any new stimuli at all in this case. At moment $t = T_2$, the central nervous system again switches over to receiving new stimuli, which begin to enter at moment $t = T_3$. The time interval $0-T_3$ completes one recurrent operation cycle of the control system of the operator.

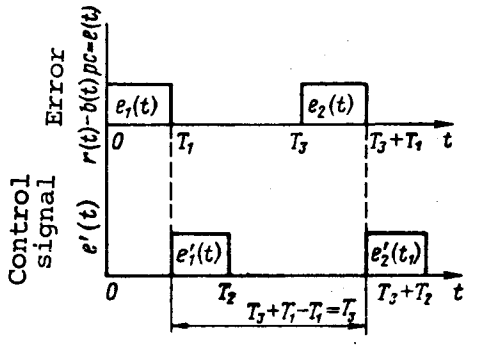

Fig. 11.1. Control signal and error.

It sometimes is considered that, using the operator transfer function, all the remaining (engineering) links of the control system can be calculated. It is forgotten in this case that the operator transfer function itself is defined experimentally during his operation in a specific system. Of course, a transfer function determined in this way characterizes the action of the operator only in this system, and, for other control systems and for other conditions, his activity requires new experimental investigations of the transfer function.

By means of training, the operator can reach the stage in which his transfer function approaches any (it stands to reason, within certain limits) state assigned in advance. In other words, the operator does not have one specific transfer function, but he can "adjust himself" or learn to operate in accordance with any function of a certain class. In the opinions of some specialists [57, 88], the operator-AC system is more reliable than a completely/47 automated system, especially under conditions of prolonged flight (Fig. 12.1). Certainly, the operator cannot go beyond certain natural limits, for example, increase the rate of reaction above his natural maximum rate or make fewer errors in reading instrument indications than that which corresponds to his visual acuity, etc. Remaining quantitatively "limited," the operator has extremely flexible characteristics; therefore, he easily adapts to any machine and to any operation. True, different operations require different intensities of force of him: physical and intellectual (attention) and, therefore, cause more or less fatigue. Therefore, despite the presence of valuable universal operator capabilities of adaptation, in planning a system, the characteristics of the control system must be "adjusted" to the psychophysiological capabilities of man, just as the geometric dimensions of the system and the forces necessary for control of it are adjusted to the dimensions of the human body and its energetic capabilities [27, 29].

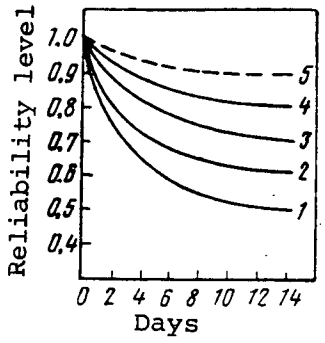

Fig. 12.1. Change in reliability of spaceship control systems, completely automated, with two-, three-, four- and five-fold duplication (1-4) and including man (5).

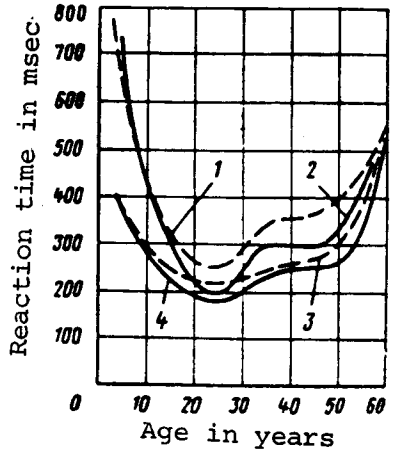

Fig. 13.1. Human reaction time: 1 - reaction time of a woman to light; 2 - reaction time of a woman to sound; 3 - reaction time of a man to light; 4 - reaction time of a man to sound.

The operator, whose responsibilities include control of the machine, to a specified degree and in specified functions, can act as a simple amplifier, as a simple differentiating link, as a single or double integrater, as an inertial link, as an ideal discrete data selection unit and as a logical filter. For example, during flight in an aircraft, the time for the pilot to begin correction of one flight mode or another after a deviation arises in an appropriate parameter fluctuates within very wide limits, from 2.5 to 65 sec (depending on the task facing him, on the magnitude of the mismatch in the parameter he controls, the rate of change in it and the sequence of introducing corrections he adopts, and other things). The reaction time of the operator depends on sex and age (Fig. 13.1). /48

The time for solution of abstract and logical problems is determined by the number of problems solved, the number of conditions under which problems were given, the number of possible solution variants, the nature of the algorithms and level of mastery of them, the necessary speed of solution, the possibilities of checking the solution, fatigue, and so on and so forth.

Certain static and dynamic characteristics of an operator, recorded under atmospheric flight conditions and during modelling of a number of space flight conditions, from the data of a number of authors [2, 72], are presented in Table 1.

The operator generates the greatest force in the direction to the body, and he generates this force easier sitting than standing. The force is increased if the entire arm and shoulder act, whereas, if one finger participates in the effort, considerably less energy is expended. The repulsive force reaches a maximum value at 40 kgf. Precision of control of an applied force is identical for the arm and leg. The arm usually moves more rapidly horizontally than vertically.

The operator performs a counterclockwise rotary movement more easily with the right hand and clockwise, with the left one. Continuous curvilinear movements are performed with greater speed than movements with sharp changes in direction. The operator /49
accomplishes free swinging movements with greater speed and with less expenditure of energy than restricted movement. Pushing is performed more accurately than moving, but, when necessary to combine pushing with movement, this takes place still more accurately, as a rule.

TABLE 1. CERTAIN OPERATOR CHARACTERISTICS

Characteristics	Value
Visual analyzer throughput capability, units/sec	12 according to Sperling 24 according to Mueller 50 according to Shiklan 70 according to Glazer and Zukerman
Time for perception of instrument readings	0.2-0.8 sec
Frequency of successful processing of input signals by operator	Not more than 3 radian/sec
Dark adaptation time	30 min
Light adaptation time	6-8 min
Mean time required for aiming the eyes and focusing them on a new point	167 msec
Visual analyzer time constant	170 msec
Operator reaction time to rapidly changing light signals, with interval between signals 0.57-2.91 sec	0.25 sec
Limiting intervals between signals, at which adequate operator reaction is possible	0.5 sec
Visual acuity, resolving power directly ahead of the operator	0.5-1 angular min
Same, under flight conditions	3 angular min
At 10° angle to the side	10 angular min

TABLE 1. CERTAIN OPERATOR CHARACTERISTICS (CONTINUED)

Characteristics	Value
At 30° angle to the side	24 angular min
Angular velocity resolving power	$\geq$ 0.3 angular min/ /sec
Reduction in visual acuity during vibrations	25% /50
Illumination perceived by the eye (apostilb):	
Minimum	10^{-5}
Greatest (blinding begins afterwards)	10^{5}
Time of transmission of light stimulus to the brain	0.03-0.3 sec
Object identification time	Up to 0.5 sec and more
Time required for making a decision	Up to 1 sec and more
Reaction time	0.25 sec
Time for determination of spatial position of aircraft (from Gerathewohl)	
By instruments	1.55 sec
Visually	1.35 sec
Limiting values of flight parameters at which pilot considers that aircraft is flying horizontally:	
In lateral bank	15-25°
According to angular turn rate	3°
According to vertical speed	10-20 m·sec
Sensory-vocal reaction time	1.5 sec
Lower movement perception threshold:	
Relatively immobile object	1-2 angular min/sec
In other cases	15-30 angular min/sec
Latent period:	
Simple optical perception (according to Rouse)	0.02-0.03 sec
Peripheral perception	0.1 sec
From formation of peripheral stimulus to foveal (central) vision	0.43 sec

TABLE 1. CERTAIN OPERATOR CHARACTERISTICS (CONTINUED)

Characteristics	Value
Time for reading instrument indications under conditions simulating orbital flight:	/51
Geographic coordinates	7.7 sec
Microclimate parameters	2.2-3.1 sec
Display light signals	0.8-1.2 sec
Operator neuromuscular reaction delay time	0.1-1 sec
Effectiveness of effort under conditions simulating orbital flight:	
During movement towards self	27 kgf
During movement from self	18 kgf
During rotating movements	3 kgf
Normal hearing range	20-20,000 Hz
Sound intensity value causing:	
Unpleasant sensations	120 dB
Onset of pain	130 dB
Appearance of appreciable illness	140 dB
Time for recovery of normal hearing acuity after the action of noise with an intensity of 120 dB for a period of 1 hr	5 hr
The same, for a period of 4 hr	20 hr
Maximum value of stretching effort by operator:	
Steady	30 kgf
Short-term	100 kgf
Nonfatiguing efforts:	
For the arm	12-18 kgf
For the leg	25 kgf
Power generated by operator for a period of 1 min:	
With the arms	0.3 hp
With the legs	0.58 hp
For a period of 0.1 min:	

TABLE 1. CERTAIN OPERATOR CHARACTERISTICS (CONCLUDED)

Characteristics	Values
With the arms	0.6 hp
With the legs	1.0 hp
Decrease in strength of arms (in 81% of cases) from initial level (45-60 kgf) under conditions simulating orbital flight	4-16 kgf
Number of movements per second without load:	
Arms	5
Forearms	78
Wrists	11-12

/52

In individual cases, vocal signals have advantages over motor ones. Movement of the vocal chords takes place with greater speed than movement of the arms (legs), and vocal signals have been studied well in information theory. Research has shown that the frequency spectra of the voices of different people, pronouncing one and the same phrase, vary within wide limits (just like handwriting). Thus, the construction of machines reacting to speech depends on the general problem of pattern (symbol) recognition.

Many investigators have determined that the operator in the man-machine system, including aboard aircraft, will operate in the best manner only in the case when he fulfills the role of simple amplifier.

If the task of the operator consists, for example, of bringing a certain object observed by him into coincidence with a desired position of it and, in this case, the operator acts on a control (for example, on the control stick), he will cope with his task in both the case when the position of the control stick determines the position of the object controlled by him and in the case when the position of the control stick corresponds to the speed or acceleration or a combination of position, speed and acceleration of the object. In each case, the operator must learn, /53 acquire experience, i.e., bring his skill to the stage where it is not necessary for him to consider what action to undertake, for the reaction to arise automatically, without reflection, sooner than he could analyze what he is doing.

The simplest functions, the optimum for the operator, are control functions where the force applied to the control is

proportional to the magnitude of error. This provides the best operating characteristics, since what psychology calls stimulus-response completeness with a 1:1 ratio is achieved here between stimulus and perception. The operator always knows that he must make this same response to one and the same stimulus and manipulate the controls similarly under identical conditions. In those cases when the aircraft operator is placed under more difficult conditions (for example, when he must fulfill the role of single or double integrating link, differentiating link and others), which is manifested especially while he is executing the function of aircraft control on a planned flight path, the accuracy of his work in the control system deteriorates.

In evaluation of the psychophysiological capabilities of the operator in control, the problem of the volume and rate of processing data coming into the operator does not take last place. It is clear that an AC operator, perceiving and processing data from the outside world (ground landmarks, horizon, instruments, signal indicators, radio communication lines and other things), cannot have an unlimited throughput capability.

Any information characterizing the condition of a process or system is called data. In purely automatic systems, data is easily evaluated. The mean value of a quantity of data in an absolutely authentic report on the condition or events of a controllable process equals the entropy of these conditions characterizing the uncertainty of the phenomenon.

The data entropy is a measure of the missing data, which changes each time for the operator after he receives data on quantities being examined. (This change in data entropy must not /54 be confused with change in entropy of the state of a process taking place during the control process. Change in entropy of the state of a process is an objective characteristic of the flow of the process, and it is determined by well-known formulas.) The amount of data used by the operator in the control process, in our opinion, cannot be determined by normal probability methods. The value of the data for the operator must also be taken into account.

Statistical data determination is based exclusively on the rarity of a situation. If a situation is encountered rarely, information of its onset contains a large amount of data. In this case, no distinction is made between data which are useful or useless for the operator, i.e., the value, meaning and significance of the data for the operator are completely ignored.

The content and meaning of the message received is more important to the operator than its probability. But how is a measure of the interest, value and importance of the message

introduced? How is semantic analytical data studied? One and the same piece of data, as a rule, has a different value for different receivers. In statistical information theory, it is considered that the receiver is capable of extracting all of the data transmitted to him by communication channels and that he evaluates precisely this greatest quantity of data. The question here is of the potential capability of extracting a certain quantity of data from a given message, and not of what data a fully specified receiver is capable of extracting from an incoming message. At the same time, the capacity for extracting data from a message depends on the store of information which the receiver of the message has.

Unfortunately, those criteria of evaluation of the quantity of data which have been worked out in information theory for solution of technical problems cannot be used for the purposes indicated above. This is explained by the circumstance that the "human factor" of perception of the value of data has been consciously excluded in determination of the quantity of data (for elimination of sujectivism in the evaluation). A formal definition of the quantity of data, excluding the concept of its value (in the human sense), completely scientific and effective for evaluation of coding devices, communications channels and other technical /55 means, is unsatisfactory for the purposes of engineering psychology, which is occupied with research precisely on the capabilities of man.

In all probability, therefore, as well as because of different conditions of "presentation" of data and the use of various methods of coding, there is a great discordance in the values characterizing the quantity of data per unit time which the visual analyzer of the operator can receive and process. If the quantity of data (in the statistical sense) is an absolute value, the significance of the data for the operator must be a relative value, having a different value for different observers, in accordance with their capacities for understanding data and using it in subsequent control activity. The quantity of data (in the statistical sense) always is a positive value; the significance of the data for the operator can be zero or negative. For example, upon entrance of a command into the auditory analyzer of the operator, in a language unknown to him, the significance of the data for the operator equals zero. If the pitch-and-bank indicator in an aircraft, instead of the actual right bank of the aircraft, shows a left one (or the operator himself takes this reading as a left bank), the significance of the data for the operator can be considered negative in this case. The significance of data for an operator, therefore, could be determined as the increase in probability of achieving the purpose for which the data is collected.

With less significance of data for the operator, a greater memory volume is required of the operator and, consequently, the

longer his training, necessary for a specific stimulus of the sense organs of the man and his data processing system.

The necessity arises, in determination of the significance of incoming data to the operator, to introduce specific coefficients into the incoming messages, characterizing their value, as well as the extent to which they are perceived by the operator. The onboard fire alarm, for example, should be recalled here. It operates by an elementary double system and, on the average, gives a comparatively small quantity of information (in the statistical sense), although it is obvious that, from the point of view of its significance to the operator, the data given to him is great. /56

Development and optimization of the operator-AC system, as a rule, is accompanied by research on the distribution of functions between the operator (operators) and automatic devices in future systems. This distribution of functions is carried out on the basis of knowledge of the positive and negative properties and characteristics of the operator and technical devices, taking the working conditions of the operator in flight into account.

Engineering psychology, as well as automatic control theory, give the necessary initial data for these purposes. We present them below; however, not to oppose the operator to the machine, but to combine them in a single man-AC biomechanical system.

Data Sensing and Processing

Machines are "sensitive" to various external stimuli within wider limits than an operator. For example, they can "react" to radiowaves of various bands and infrared rays, which are inaccessible to the operator. On the other hand, machines are not subject to the effects of such factors as boredom, fear, uncertainty, irritability, prejudice, deceit or illusions, which frequently throw the operator "off balance."

An operator, in contrast to a machine, can comparatively easily identify various shapes, produce a generalization on the basis of them (combine them into an entire picture), detect signals in loud noises (select the necessary data), is capable of using inadequate (incomplete) data and of creating a complete representation from separate events, take good account of the probability of events and predict their development, even with a shortage and distortion of information.

A machine is capable of calculating exactly, without error and rapidly, possesses deductive logic (is capable of fulfilling instructions as to the processing of data and of "going" from the

general to the particular), of carrying out extremely complicated operations over various functions and possesses a very high throughput capacity for data processing per unit of time [1, 13, 58, 72].

An operator is capable of correlating particular events (can think inductively), can make judgments, is capable of independently making decisions and planning actions under conditions of a sudden lack of data, in a constant or arbitrarily changing situation, and can quickly generate and use flexible programs. An operator has a high selectivity (sifts out unnecessary data), is capable of self instruction, practice, formation of concepts, of judgment and analysis, of interpretation of unlikely and incompatible events and is capable of organizing and combining input readings of various modalities and parameters. He has been imparted the gifts of creativity, improvisation and initiative [42, 43]. /57

A machine can easily store data in "convoluted" form and is completely free of unnecessary data, it has an increased "memory" over short periods of time and is capable of recovery of a large amount of data. An operator is capable of selectively performing and of extracting useful results from experience (taking account of accumulated knowledge) and can possess a large volume, long term memory [13].

Action

A machine has the capability of directly controlling large, practically unlimited power, smoothly, uniformly and precisely applying great force, has high speed, little delay, high accuracy of control during the action of external disturbances, reacts to any required derivative or integral of a controllable parameter or combination of them, with any desired degree of feedback, to guarantee a given quality of control, precisely carries out multiple, repetitive, standard and stereotyped operations and actions, without deterioration of operating characteristics, does not know "fatigue" "fear" or "distraction of attention," does not reduce efficiency as a consequence of "fatigue," has outstanding "watchfulness," including during the waiting mode, and is constantly prepared for action.

An operator, in some cases, can unintentionally, under the influence of external conditions, disturb the mode of operation of the system and degrade its characteristics. An operator, as a rule, can restore the efficiency of a system during a breakdown better than any automatic machine, and find approximately correct solutions in unforeseen cases.

An operator is capable of operating comparatively successfully in unexpected, unforeseen situations, has great flexibility and adaptability to external influences, has a very high resolving power under especially difficult conditions (stress), operates in new situations according to the circumstances and not by previously developed algorithms, and he can operate according to many programs. An operator himself can select the tempo of operations according to conditions (selective attention and action), is capable of adapting to actions in a wide range of situations, has pliability and flexibility of action, is capable of solving one and the same problem differently (achievement of the final goal by various routes), of rapidly using reserves and correcting errors (flexible self-programming). An operator has the capability of carrying out resourceful actions, of improving himself in proportion to his training, of periodically recovering his strength, and has the capability of "extraction" of new information (researcher). An operator is the most important, chief element of the operator-AC system: he monitors the operation of the system, reorganizes it, approves or records decisions "adopted" by the machine and raises the reliability of the entire system. /58

Proceeding from the psychophysiological capabilities of the operator under flight conditions and the characteristics of the technical components to an improved stage of development of aviation and astronautics, an optimum mutual combination of the operator and technology is necessary in operator-AC systems.

In general, two groups of tasks are placed on operators in aircraft (airplanes, spacecraft for various purposes), for solution of which in fact man "is included" in the spacecraft and aircraft control system.

In the first group are those tasks which, at the contemporary level of development of technology, absolutely cannot be carried out by technical means.

In the second group are those tasks which can be accomplished in equal measure by both man and automatic devices. However, by "transposition" of accomplishment of these tasks to the operator, the efficiency of the AC can be increased in a number of cases, because of the reduction in weight, dimensions and power requirements of technical means, reduction in cost of the system, and, to a considerable extent, increase in its reliability. Division of functions between the operator and the machine should be approached comprehensively and quite cautiously in these cases. In particular, there are problems, the accomplishment of which, at first glance, can be entrusted to man, but they require absolute, prolonged readiness and vigilance of the operator. These requirements come into conflict with the basic mechanisms of operation of the psychic and psychophysiological systems of man, and, consequently, compel the solution of such problems with the aid of an automatic (mechanical) system. /59

In particular, in development of aircraft flight control systems, it is necessary, for elimination of manual flying errors, to change to semiautomatic flying (landing and touchdown).

Actions to counter situations arising unexpectedly for the pilot, the action of horizontal and vertical wind gusts, as well as prevention of entry of the aircraft into critical modes (restriction of bank angles and overloads, angles of attack and slip, angles of deflection of the control surfaces and their rates of movement), must be automated. Besides this, automatic devices must "accept" tasks in improvement of control of movement of the group of aircraft (control of the rate of arrival of aircraft, assembly and break-up of groups, landing patterns of aircraft at air fields, control of aircraft on flight paths assigned by ground points).

Automatic devices must guarantee high reliability of orientation (navigation), freeing the crew from fatiguing and essentially monotonous calculations.

It probably is advisable to free the operator of fatiguing actions in orientation of an aircraft, from navigational calculations, from maintaining the aircraft in a given position (stabilization), from carrying out complicated calculations for accomplishing a maneuver and from other operations, in which the operator cannot display his capabilities, which the capabilities of modern automatic devices would surpass.

Evaluation of Operator-AC System

Efficient distribution and combination of the functions of man and the machine and the development of the principles of various system structures and their most efficient exploitation require evaluation of a system, not only from the engineering and economic points of view, but from the position of psychology and physiology. /60

In the theory of automatic control, effective methods of evaluation and investigation of control systems have been developed; however, they cannot be unconditionally adopted for the operator-AC system, since they do not take into account (and cannot take into account) the psychophysiological stress of work of an operator in the operator-AC system, without determination of which it is impossible to evaluate such a system.

Practical psychology has accumulated many methods, relating to research on individual elements of a closed control system (methods of investigation of the readability of the scales of individual instruments using tachistoscopes and determination of

time and accuracy characteristics of the operator; investigation of simple and complex sensorimotor reactions of the operator; and a series of other methods).

However, they cannot always help in investigation of closed control systems. They are most suitable of all for "systems with observers," rather than for "systems with operators." In the latter, the operator not only perceives data, but actively and purposefully changes it. And operator-AC systems, as a rule, are not "systems with observers."

It can be considered established that separately existing psychological, physiological and engineering methods of research on control systems with operator partipation do not permit an objective evaluation to be given of one system or another, with consideration of the degree of psychophysiological stress on the operator.

Therefore, the necessity arises for development and proving of new, more effective methodical procedures of investigation and evalution of control systems with operator participation, which are the most suitable for conditions of operation of the systems in aviation and space flights. Together with the study of individual psychic functions, their use also assumes the conduct of experimental research, under conditions of reproduction of, if not the entire set of factors acting on the operator and the system, at least the most significant set of them. In this manner, research must be carried out on dynamically similar models /61
of control systems, with reproduction of flight conditions or directly under flight conditions.

Similar modelling test units were used earlier in research studies of flight work.

The necessity for evaluation of variants of control systems (and, of course, of all engineering elements included in it) still in the design stage, before its release for production, also is important. All of this has compelled specialists to reach the following basic position.

Development of new AC systems with operator participation, study of their characteristics and improvement, taking account of the psychophysiological capabilities of the operator, must be carried out on the basis of comprehensive research, not only of individual elements, but mainly of the operator-AC biomechanical system as a whole, under conditions of coupled actions of the operator and the automatic apparatus.

Study of operator-machine interaction in complex, closed AC control systems, is possible at present mainly by experimental methods.

The circumstance that, in general engineering psychology, calculation methods of analysis and synthesis of control systems with operator participation, similar to those which have been developed in automatic regulation theory for technical regulation systems, still have not been developed, must be fixed in this means of research. Under these conditions, extensive development of empirical experimental investigations, which permit the accumulation of facts, their systematization and correlation, which ultimately assist in development of calculation methods of creation of control systems with operator participation, is necessary.

An extensive group of methods is used under experimental conditions, physiological, hygienic, experimental-psychological. However, cybernetic methods can and do give the greatest effect. They permit investigation of the characteristics of the entire control system, determination of the functional capabilities and limitations of the operator, during his interaction with the machine in the control process, in modelling closed control systems with operator participation.

Final results and conclusive judgments on the properties of one control system with operator participation or another positively must be given by research, set up under actual AC flight conditions. /62

Modelling of actual processes with the aid of analog computers is one of the basic methods of planning and working out an AC control system. It continues during the entire time of experimental working out of the systems indicated.

In proportion to development of a control systems, models can become closer to an actual system, if the mathematical analogs of individual elements are replaced by real specimens[2].

Problems of the functional reliability of the man-machine system, applicable to flight conditions, can be investigated on these models. In particular, it is necessary to investigate the change in functional characteristics of a human operator in the process of his AC control activity. These investigations assist in determining the time, during which the functional characteristics of the operator do not undergo significant changes, in comparison with those for which the control system was calculated.

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[2] There are hypotheses, according to which investigations of control systems can be carried out in those cases when a dynamic model of the systems is supplemented by a model of the operator. It is true that these methods still have not been widely developed.

A whole set of investigations can be carried out in determination of the characteristics of an operator as a "live component" of the AC control system. Particular attention should be given, during use of such models, to investigations, directed towards development of requirements for reactions by an astronaut, setting forth specific features of control of the aircraft.

Depending on the nature of utilization of modelling devices, mathematical and physical modelling can be distinguished.

In mathematical (or total) modelling, an AC control problem is presented completely in mathematical form; the equations obtained are fed into a computer and their solutions are determined by use of it.

In physical modelling (sometime also called partial or test), only part of the system is set forth in mathematical form, i.e., /63 is modelled, and the other part is present in the form of actual components of the control system.

The first type of modelling has the advantage that it permits utilization of any convenient time scale. Its shortcoming is the necessity for complete mathematical formulation of the problem.

In the second type of modelling, this shortcoming is eliminated, but solution of the problem is possible only on the real time scale; otherwise, actual elements of the system cannot be included in the modelling test stand. Sometimes, this requirement can be extremely rigid for modelling apparatus, since its errors usually are irregular functions of time.

Besides modelling, in which integration of a system of differential equations, describing the dynamics of the object of control, is carried out, in the modelling test stand, the control system includes special devices simulating actual flight conditions, in which elements of the control system and the operator operate (for example, a cockpit is installed in an actual centrifuge and other things).

In investigation and comparative evaluation of AC control systems with operator participation, as a rule, the second type of modelling is used.

As an example, let us examine two modelling schemes for AC control systems.

Modelling a System of Control of an Aircraft on the Let-Down Flight Path Through the Glide Path Leg

In working out a command (director) control of an aircraft landing by a glide path beacon, groups of systems for blind instrument landings, perhaps first acutely presented the problem of carrying out investigations with operator participation in a dynamic model of an aircraft, using ready-made units of a director control system.

A block diagram of a modelling unit and a functional scheme of modelling a flying-navigation director system for landing are presented in Fig. 14.1 and 15.1. Such schemes were used in carrying out research on director systems. In these schemes, almost all the devices are presented which are necessary for /64
research on a control system, with the possible exception of devices determining the quality of work of the operator in control of the aircraft. The medical apparatus unit actually consisted only of a pulse-beat recorder, and, by inclusion in the scheme, it absolutely was not intended to use it for integral evaluation of the control system.

Modelling Dynamics of Control of Aircraft Orientation

The control process is modelled with the aid of an analog computer, from which signals, characterizing the state of the process being controlled, enter the indication and signalling system. The operator obtains information on the condition of the process being controlled, produces control signals and, thereby, changes the process being controlled and its coordinates. A block diagram of the modelling test unit is represented in Fig. 16.1.

Recording devices for registering the control dynamics are switched in to the modelling units. Motor and vocal reactions /67
are recorded by the reaction recorder. There is a device in the system for recording the biological currents from different sections of the functional systems of the operator. A spectral analyzer is used for analysis of the encephalograms, permitting curves with various frequencies (rhythms) to be extracted from the aggregate encephalogram. Integrators provide determination of the mean level of each frequency component of the enccephalogram over selected intervals of time. In the system, there also is a computer of control quality, determining it by integral evaluations of the transition processes.

In selection of a method of evaluation of the operator-AC system, it should be kept in mind that, in investigation of the functional characteristics of man under conditions of work in an

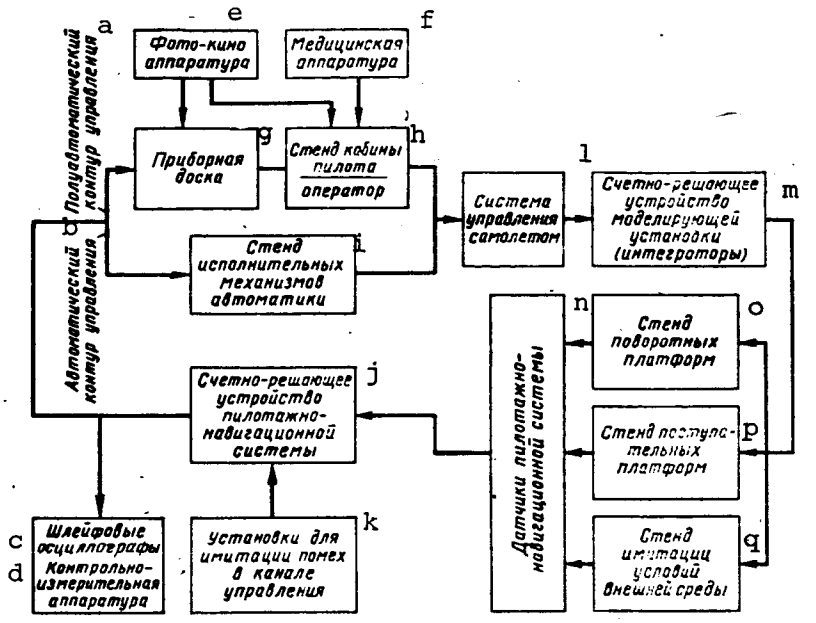

Fig. 14.1. Modelling unit block diagram.

Key: a. Semiautomatic control circuit; b. Automatic control circuit; c. Loop oscillographs; d. Monitoring-measurement apparatus; e. Movie camera; f. Medical apparatus; g. Instrument panel; h. Cockpit test unit, operator; i. Automatic actuating mechanism test unit; j. Flying-navigation system computer; k. Unit for simulating interference in the control channel; l. Aircraft control system ; m. Computer modelling units (integrators); n . Flying-navigation system sensors; o. Turning platform test unit; p. Translational platform test unit; q. External medium conditions simulation test unit.

AC, determination of the capabilities of the operator to receive and process data, coded as a rule, coming to him through various analyzers, is important. The introduction of quantitative estimates of the data which an operator can process in a unit of time, under various functional loading conditions on the operator would permit a relatively quantitative characterization of the psychic stress on the operator to be given, during work at various stages of flight, and requirements for the most effective methods of coding data to be determined, since the rate of perception of data by the operator can serve as a measure of effectiveness of the coding system.

Unfortunately, those criteria of evaluation of the amount of data, which have been worked out in information theory for solution of technical problems, cannot be directly used for the purpose indicated above.

The method of evaluation of the operator-AC system should provide, not only a comparative evaluation of the system with respect to its dynamic and static technical characteristics (final purpose of control), but an evaluation of the psychophysiological stress on the operator during his work in the specific control system. A special generalized (or integral) method can be used for investigation and evaluation of the man-machine system. Under

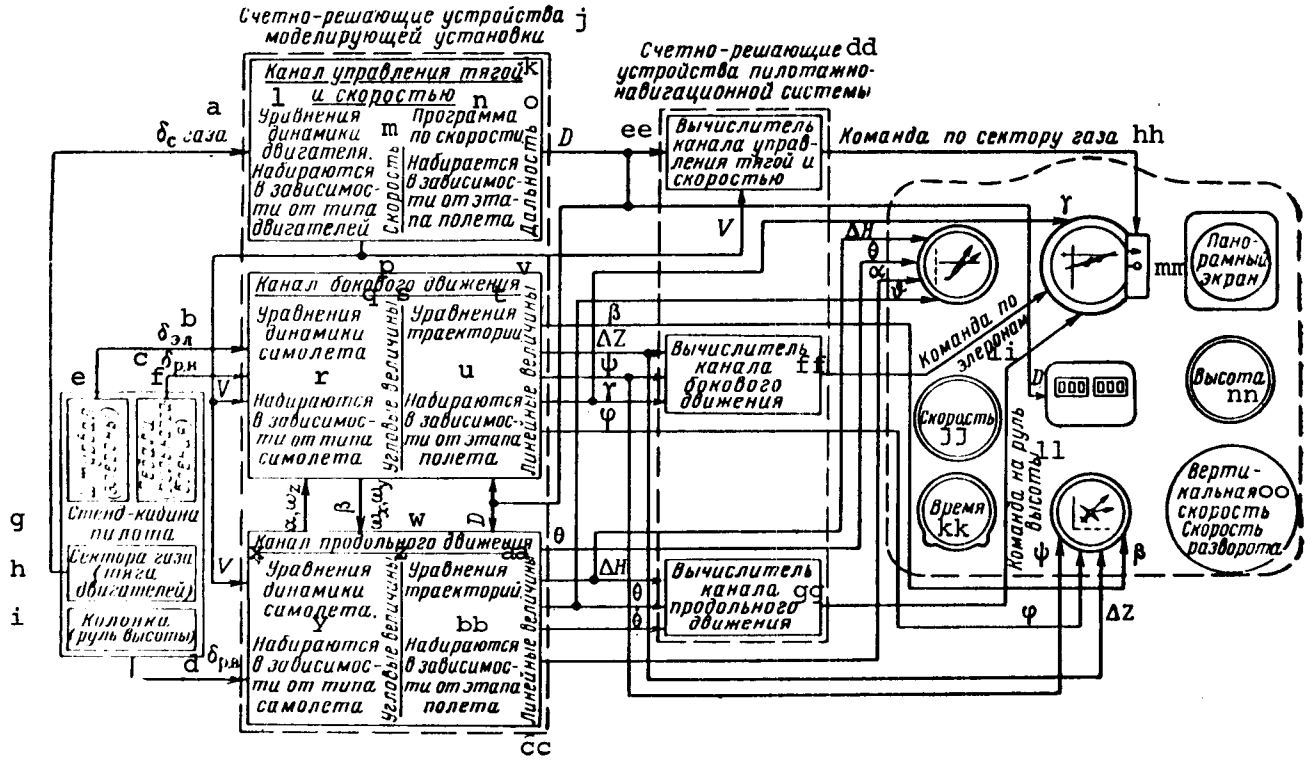

Fig. 15.1. Functional scheme of flying-navigation system modelling.

Key: a. δ_t gas; b. δ_{el}; c. δ_{rud}; δ_{elev}; e. Control stick (ailerons); f. Pedals (rudder); g. Cockpit test unit; h. Throttle (engine thrust); i. Control stick (elevators); j. Computer modelling unit; k. Thrust and speed control channel; l. Engine dynamics equations set up depending on engine type; m. Speed; n. Speed program set up depending on flight stage; o. Distance; p. Lateral movement channel; q. Aircraft dynamics equations; r. Setup depending on aircraft type; s. Angular values; t. Flight path equations; u. Setup depending on flight stage; v. Linear values; w. Longitudinal movement channel; x. Aircraft dynamics equations; y. Setup depending on aircraft type; z. Angular values; aa. Flight path equations; bb. Setup depending on flight stage; cc. Linear values; dd. Flying-navigation system computers; ee. Thrust and speed equations computer channel; ff. Lateral movement computer channel; gg. Longitudinal movement computer channel; hh. Throttle command; ii. Aileron command; jj. Speed; kk. Time; ll. Elevator command; mm. Panoramic screen; nn. Altitude; oo. Vertical speed turning rate.

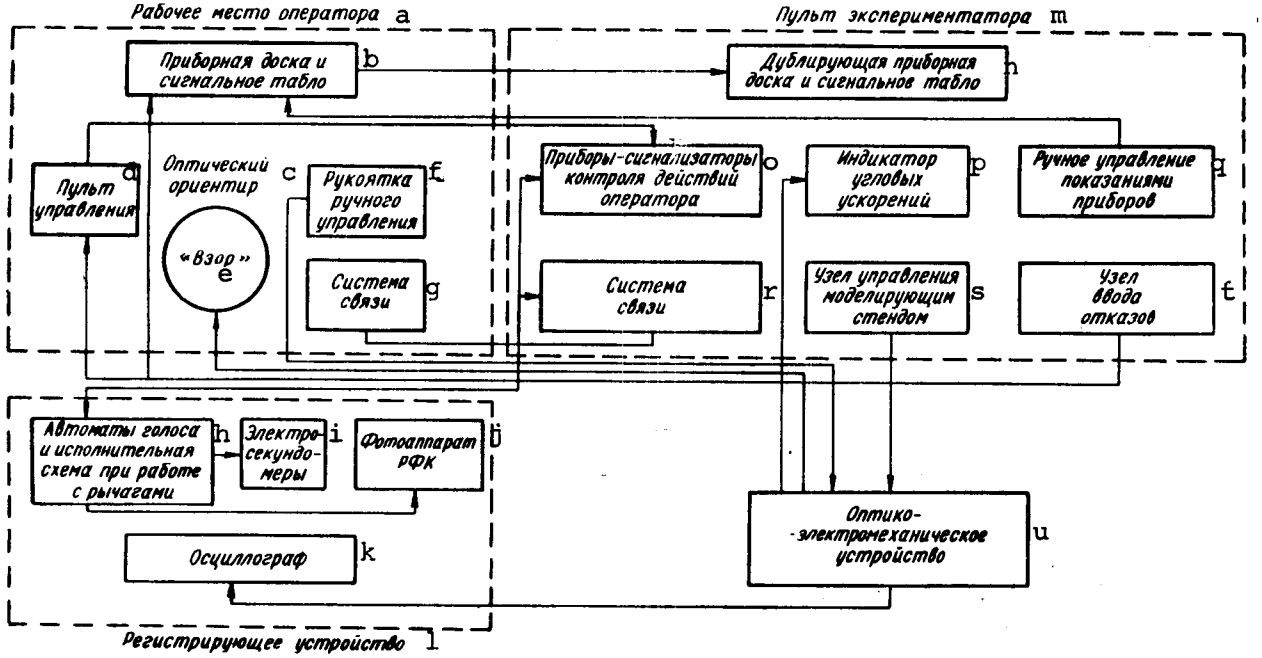

Fig. 16.1. Modelling test unit block diagram.

Key: a. Operator work place; b. Instrument panel and signal display; c. Optical indicator; d. Control panel; e. "Look;" f. Manual control lever; g. Communication system; h. Voice and actuating system automatic machines during operation with levers; i. Electric stopwatch; j. RFK camera; k. Oscillograph; l. Recording layout; m. Experimenter panel; n. Duplicate instrument panel and signal display; o. Operator action monitoring instrument-signal indicators; p. Angular acceleration indicator; q. Manual control instrument readings; r. Communication system; s. Modelling test unit control unit; t. Breakdown introduction unit; u. Optical-electromechanical device.

these conditions, scientific experiment is indispensible, and only those methodical procedures can be suitable, which basically follow the recommendations that study of the activity of man in /68
carrying out one operation or another should not be carried out in isolation, but in combination with the system in which the operator must work.

The question is introduced in engineering-psychological research as to the criteria by means of which one control system or another with operator participation is characterized.

Evaluation of a manual control system with operator participation cannot be restricted only by indications of the control process dynamics (transitional functions, their nature, time of the transitional process, errors in forced and established modes, precision of accomplishment of a given process). Such characteristics as expenditure of energy in control, the number of erroneous actions by the operator, the time characteristics of his work activities (latent period of operator reaction, time for accomplishment of one operation or another) should be included here. Evaluation of some systems, for example, during transmission of digital data by the operator, can be carried out according to the time expended in data transmission, the number of symbols transmitted during a continuous time of operation and the number of errors made. Moreover, and this is most important, in evaluation of a system with operator participation, the psychic stress on the operator, determined from data of a set of recordings of electrophysiological indicators, must be taken into account, and the dynamics of formation of the operator skills in control of the system must be taken into account as well.

A multiple (polyeffector) method of evaluation of the man-AC system (Fig. 17.1) has been constructed by reproduction of the actual dynamics of the AC control process, simulation of the external working conditions of the operator, registration of the quantitative and qualitative control processes, as well as registration and analysis of the electrophysiological indicators of the operator, taking into account his neuropsychic stress and determining the dynamics of skill formation [61, 63].

In working in a complex control system, together with such indicators, characterizing the appearance of emotional stress in the operator as gripping the control stick, the presence of sudden, disproportionate and uncoordinated movements, constriction of the attention span, inadequacy in its distribution and switching, /70
the electrophysiological indicators undergo significant changes.

Therefore, in the method being discussed, the following are used as electrophysiological indicators:

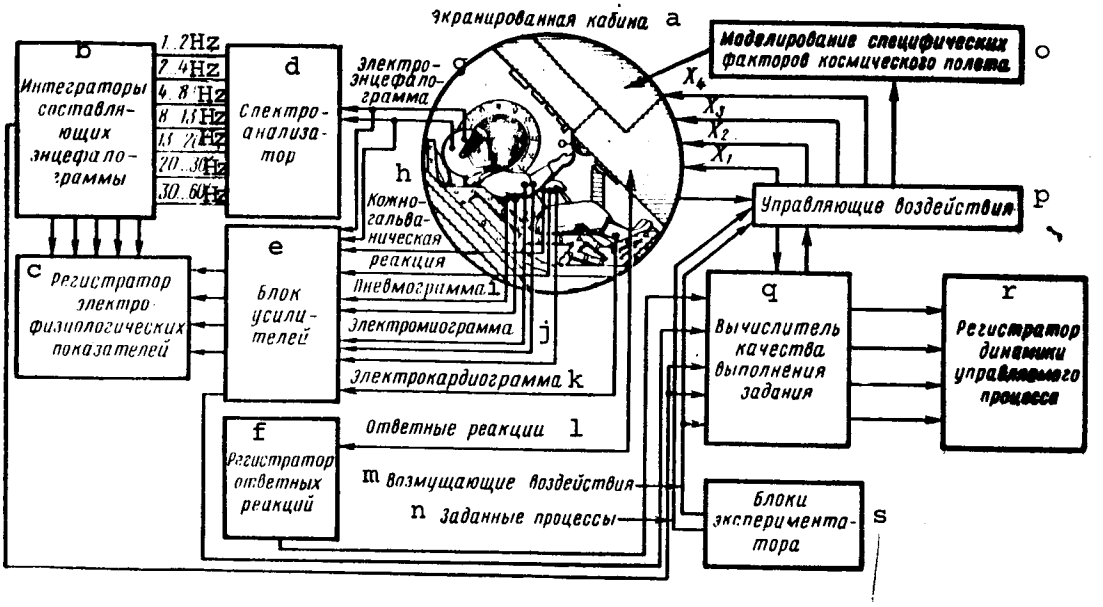

Fig. 17.1. Schematic diagram of evaluation of man-machine system.

Key: a. Screened cabin; b. Encephalogram component integrators; c. Electrophysiological characteristics recorder; d. Spectroanalyzer; e. Amplifier unit; f. Reaction recorder; g. Electroencephalogram; h. Galvanic skin response; i. Pneumogram; j. Electromyogram; k. Electrocardiogram; l. Reactions; m. Disturbing actions; n. Planned processes; o. Simulation of specific space flight factors; p. Control actions; q. Tasks accomplishment quality computer; r. Controllable process dynamics recorder; s. Experimenter's unit.

a) Mean indices of bioelectric activity of the cerebral cortex, from electroencephalogram (EEG) data. The EEG is an electrical oscillation, ranging from a few to 100 Hz and more. The greatest importance is attributed to the δ_2, δ_1, θ, α, β_1, β_2 and β_3 waves.

The δ_2, δ_1 and θ waves are slow oscillations, with frequencies of 1-8 Hz and amplitudes of 20-100 μV and more. These waves characterize the predominance of an inhibiting process in the cerebral cortex (distinctly expressed in the somnolent condition and sleep).

α waves reflect the condition of normal synchronization of the basic neural processes and are dominant, making up the basic biopotentials of the brain of a healthy waking man (their frequency 8-13 Hz, amplitude 50-100 μV).

β_1, β_2 and β_3 waves are oscillations with frequencies of 13-60 Hz and an amplitude of 20-70 μV. Predominance of these waves indicates a stimulating process in the cerebral cortex (they increase in amplitude and increase in frequency during physical and mental work and emotional stress);

b) Mean indices of bioelectric activity of the muscles, electromyogram (EMG). The EMG is characterized by amplitudes on the order of 20-200 μV and frequencies of 20-500 Hz. Very sudden movements can be accompanied by biopotentials with an amplitude of up to 1-2 mV. The biopotentials, as a rule, appear 0.01-0.04 sec before the motor act begins;

c) The mean amplitude value of spontaneous oscillations of the galvanic skin response (GSR), according to I. Tarkhanov [27]. The equilibrium potential difference of the skin is 10-20 mV, at a distance of 1 cm between electrodes. Oscillations up to 100 mV and more can be observed during stimulation. Change in GSR values and frequency amplitudes take place during change in functional reactions of the operator (emotional stress);

d) The mean value of the number of cardiac contractions, from the electrocardiogram (EKG) and respiration rate per minute, according to the pneumogram (PG). /71

For an evaluation of the functional condition of an operator in the man-machine system, a whole series of functional trials or tests is used. The following tests are the most widespread in research applicable to a human operator.

1. EEG tests.

a) Eye closing (EC) and eye opening (EO) test. This test is based on change in rate of transition of the brain from stimulation to rest; it is determined by the length of the latent period of synchronization (LPS) of the α rhythm upon EC, and from rest to stimulation, it is determined by the length of the latent period of desynchronization (LPD) of the α rhythm upon EO. In the opinions of a number of investigators [70], the higher the excitability of the brain, the longer the LPS and the shorter the LPD, and the lower, the shorter the LPS and the longer the LPD (Fig. 18.1).

b) Test of assimilation of rhythm of light flashes, going from 1 to 30 Hz and higher with increasing frequency. The maximum index of assimilation of the rhythm of light flashes most often lies within the α rhythm region (8-13 Hz), but in some cases, can be in other frequency ranges (Fig. 19.1). /72

2. GSR tests

Tests including the action of light, sound, thermal, tactile, propriocentric and other stimuli of various intensities and durations on the operator.

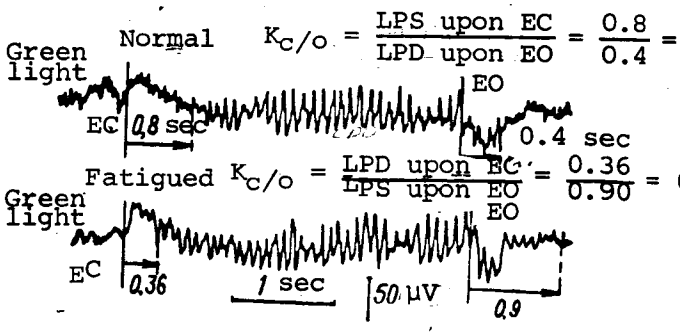

Fig. 18.1. Dynamics of latent periods of EEG reactions to closing and opening the eyes (LPS upon EC and LPD upon EO) and their ratio ($K_{c/o}$) in a normal type of EEG reaction of a healthy, unfatigued man and on a background of fatigue; the mean values characteristic of a given functional condition and the $K_{c/o}$ values are indicated by the numbers (according to G. A. Sergeyev, L. P. Pavlov, A. F. Romanenko).

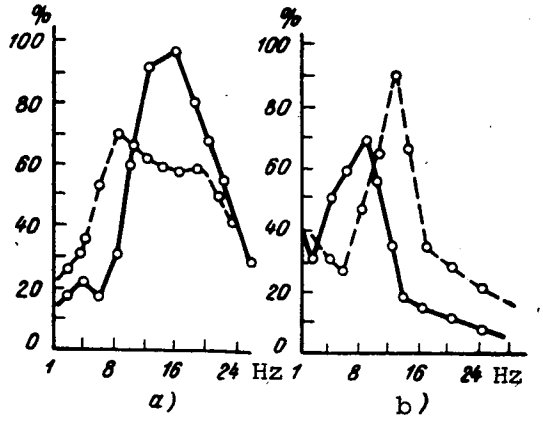

Fig. 19.1. Average data on 3 subjects, for rhythm assimilation reaction in the 1-25 Hz range with the left (solid line) and right (broken) cerebral hemispheres before beginning work (a) and on the background of fatigue after 4 h of mental work (b). Abscissa - frequency of light flashes (in Hz); ordinate - rhythm assimilation index (according to G. A. Sergeyev, L. P. Pavlov, A. F. Romanenko).

Comparison of the use of sound, light, tactile and propriocentric stimuli show that GSR, arising during use of propriocentric stimuli, die out more slowly than during use of light and sound stimuli.

During use of thermal stimuli (heat, cold), the GSR arises when they are switched on, during change in the intensity of the action and upon switching off. P. G. Shamrov [74] has showed that, during increase in emotional stress on the operator, while carrying out a task of the logical-data type, there are certain interrelationships between the EEG and GSR indices (Fig. 20.1), characterizing his functional condition in the man-machine system. /73

3. EMG tests, including various functional-loading proportioned tests (work with an expander, dynamomenter, dynamograph, etc.).

4. Tests for investigation of cardiovascular system and respiration also should include various functional-loading proportioned tests (work with expander, squatting, three-minute run, etc.).

By carrying out numerous tests, it has been established that, during work of an operator with a more "difficult" system, an increase in high-frequency rhythms of the cerebral cortex is recorded, the bioelectric activity of the muscles involved in control is increased,

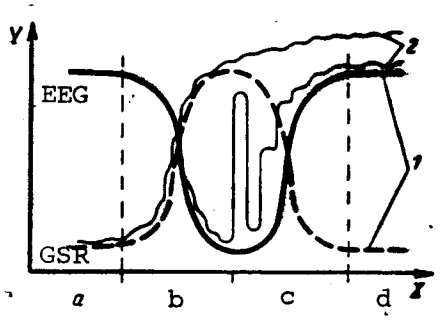

Fig. 20.1. Dynamics of change in α rhythm (EEG) and electrical potential of the skin of the wrist (GSR) during maximum mental efforts vs. functional condition of the central nervous system (CNS): Y - EEG and GSR amplitudes; X - level of excitation of CNS; 1 - specific reaction in response to mental efforts; 2 - spontaneous changes at high level of excitation; GSR becomes irregular, with low-amplitude oscillations at the level of noises; high-amplitude α rhythm spindles arise, paroxysms; a - state of rest; b, c - high level of excitation of CNS; d - overexcitation of CNS (according to P. G. Shamrov).

the amplitude of GSR oscillations is increased, as well as the cardiac contraction and respiration rates [28]. /74

In concluding the chapter, the problem of reliability of man in the operator-AC system should be decided on. To speak of the reliability of man makes sense only in connection with analysis of his activities as a "link" in one control system or another. Frequently, reliability is identified with efficiency, which is not entirely correct.

By reliability of the operator, the capacity of the operator to carry out the functions specified to him in a given system, under given conditions, without error or breakdown during a specified time, should be understood. Quantitatively, reliability (in technical systems) is evaluated by such parameters as running time to breakdown, total accrued operating time and other things, as well as by the probability characteristics (probability of troublefree operation, probability of breakdowns, breakdown rate, etc.). Paramount in reliability theory is the concept of breakdown, the total or partial loss of capacity for carrying out given functions. Operator breakdowns are stopping work under the influence of stress influences, disturbance of temporary modes of operation and errors in perception and identification, making decisions, executing control actions and other things.

Professor V. D. Nebylitsyn [60] has examined certain characteristics of operator reliability in detail and has analyzed those psychological qualities of the individual on which they can depend. Among them are "permanent" endurance, endurance under extreme stress and overstress, resistance to interference, spontaneous distractability, reaction to unexpected stimuli, changeability and resistance to the action of factors of the medium.

For the operator-AC system, the problem of insuring reliability of operator actions is one of the main ones in creation and use of the system in flight. Specialists in engineering psychology and aviation and astronautics must give a huge amount of attention to this problem, develop quantitative and qualitative criteria of evaluation of operator reliability in operator-AC systems, for the purpose of working out recommendations for selection and training of pilots and for optimization of the characteristics of the operator-AC system.

CHAPTER II. INFORMATION MODEL OF PILOTED FLIGHT /75

Piloted Flight and Engineering Psychology in Aviation and Astronautics

From the point of view of engineering psychology in aviation and astronautics, any piloted AC, civilian or military aircraft, helicopter or spacecraft, is a set of diverse technical control systems, including a human operator. Each of the systems includes a certain number of uniform elements, joined with connections in such a manner that complete functioning is provided.

Expedient utilization of an AC requires that its movement be controllable. Controlled movement of an AC in the atmosphere of earth or a planet or in outer space is characterized by a planned change in coordinates, speed and acceleration, and it is accomplished in order to achieve specific purposes. Flight of an AC can be considered as consisting of separate parts, which have their own specific tasks and which are called flight modes. A given flight mode is maintained by change in the parameters defining this mode, i.e., by appropriate changes in the coordinates, speeds and accelerations.

Flight in the atmosphere and in space should be considered primarily as a process of movement of an AC. The flight of any AC can be divided arbitrarily into several more or less specific (individual) phases. The first phase is the takeoff of the AC from earth, the second is enroute flight (orbital flight) with execution of specified mission programs, and the third is the landing on earth. For certain spacecraft, the enroute-orbital phase of the flight can be interrupted by a landing on the moon /76
or other planets, which, however, is included in the specified mission program in these cases.

Practically, in accomplishment of any phase of the flight of piloted AC, as a rule, the necessary orientation and stabilization of it in space relative to a selected direction (coordinates) must be carried out, and maneuvers must be accomplished, in accordance with the planned program and the conditions established.

For stabilization of the position of a spacecraft, it is necessary that all unnecessary rotations and oscillations relative to the axes of the coordinate system selected, disturbing the programmed orientation, be extinguished. Such rotation can take place as a consequence of various factors.

The main one of them should be considered the moment of force, which the spacecraft can produce during separation from the last stage of the carrier rocket. A moment of force causing rotation can appear as a consequence of certain, even though the slightest,

discontinuities and irregularities in discharge of the gases from the orientation and stabilization engine nozzles, and also as a consequence of a shift in mass inside the ship.

As a result of the initial rotation produced and of the irregularities in distribution of mass, the spaceship will have, although slow, quite complex rotations around its center of mass.

Maintenance of assigned modes during flight of an AC (airplanes) was accomplished before by the operator, based mainly on his own direct feelings, almost using no instrument or onboard device at all. In modern AC, having a diversity of multicircuit systems, the operator does not interact with the craft itself and does not control it directly. In essence, he proves to be "separate" from the devices and mechanisms he controls and, in fact, from takeoff to landing, he controls by instruments, monitoring their condition. Even in visual flying of AC, the instruments are used as amplifiers of the sense organs of the operator, permitting precise analysis of a range of controllable processes, which is inaccessible to direct perception (for example, comparatively high flight altitudes and speeds, thermal stress of engines, reserve of reaction mass and other things). /77

Observing the different means of representation, supplying data to the operator on the objects controlled by him, external conditions and progress and solution of problems by the control systems, acting on the system of control levers, the operator accomplishes data and energetic contact with the AC. The interrelated set of various instruments and devices, representing the actual flight situation, and system controls might be called an information model of piloted flight.[1]

General Medical-Technical Requirements for an Information Model of Piloted Flight

An information model of piloted flight must be an adequate representation of its flight characteristics and state of the object of control. Constructing an adequate dynamic information model of piloted flight is one of the major tasks of engineering psychology in aviation and astronautics. This model must contain only those properties, relations, connections and interactions of the systems controlled which are essential for control.

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[1] For an operator-AC system, in which man is not aboard the AC, but carries out the AC flight control functions from the earth, a similar set of instruments and devices on the ground control panels can be called an information model of controlled flight.

Information models of piloted flight can be of three types: detailed (differential), general (integral) and combined.

The detailed model can include detailed information of individual parameters of piloted flight. In use of the detailed model, the operator obtains a precise quantitative evaluation of the condition of the separate AC systems, subsystems and items included in them. However, in order to obtain a qualitative evaluation of the situation from the detailed model, the operator must expend comparatively much time, which he cannot always do in modern AC. /78

As a rule, the general model does not give a quantitative evaluation of the flight parameters. Therefore, an information model of piloted flight of modern aircraft or spacecraft must, as a rule, be combined, i.e., include elements of the general and detailed models.

The operator, having such a combined model at his disposal, can, quickly evaluating the qualitative flight situation, in case of necessity, use elements of the detailed model for a quantitative evaluation of the flight mode.

Experience shows that introduction of an extremely great number of elements into the detailed model can sharply change its properties for the worse, and it becomes futile; the general model, if it is made too abstract, can lead the pilot into error and also is not of value to the operator.

The information model should be graphic, provide a high rate of stimulation of the data perception and processing analyzers of the operator, i.e., have the most efficient code, and permit him to decode the information supplied to him without error and insure (when this is required) that decisions made by the operator are effectively put into practice.

The model should be "organized" so that the operator, on the one hand, does not experience unusual sensory "starvation," and, on the other, is not overloaded with secondary and essentially unnecessary data for control of the AC.

Indisputably, the characteristics of the model must be in optimum conformance with the information and also energetic characteristics of the operators. In particular, it must be seen to that the characteristics of the model are "compatible" with the muscular sensations and sense of balance of the operator, so as to decrease the possibility of loss of orientation in flight by the operator.

Solution of these problems, like the majority of problems introduced in the creation of an effective information model of

piloted flight, can be achieved by the accomplishment of much complicated research, design and experimental work. /79

As a rule, various instruments must be included in the information model of piloted flight (sensory field of the model): indicators, sights, plotting boards, graphic control panels, screens and signal indicators, as well as various manual controls of the systems and items (motor field of the model).

Information models of piloted flight, depending on the type and purpose of the AC, can be extremely diverse.

Substantiation of the most effective models of piloted flight must proceed from the features of the dynamics of the objects of control, the nature of the tasks placed on the object being controlled, the type and quality of the systems controlled, the specific conditions accompanying the flight and the number and occupations of the crew members. Nevertheless, all of them, including those which will be created in the future, must satisfy a set of common, in fact united, medical-technical requirements. They refer, first, to the volume of information given to the operator by the model.

The operator in any AC must know the AC position relative to the selected coordinate system or velocity vector (angles of pitch, bank, yaw) and, in individual cases, their derivatives (speed and acceleration). This information is necessary for control and monitoring of the AC orientation and stabilization.

For "fixing" the AC position in space, relative to a ground, air or space object, landing place, planned flight path and position over a planet, the information model is "bound" to give the operator appropriate data at any moment of its flight. In particular, it concerns: flight altitude, coordinates of the AC position relative to the selected system (or systems) of coordinates, distance to the objective of the flight, lateral deviation from the planned route and length of the course f l o w n (or remaining).

The information model must characterize the movement of the AC along the flight path by the value and direction of the speed (absolute, course, air), relative rate of approach to the flight objective, direction of entry to the objective and present flight time and that remaining to the objective. The model must without /80
fail include devices monitoring flight safety (minimum and maximum velocity head, limiting value of M number, maximum permissible G-force, minimum flight height, prevention of collisions with the earth or other AC, emergency supply of fuel or working substance and other things).

A specific part of the information model must be diverted to control of automatic and various other AC systems (autopilot, systems creating cockpit and pressure suit microclimates, electric power systems, internal and external communications systems, propulsion units for all purposes and other things).

In an AC, intended for comparatively long flights, the information model can include a group of devices supplying the operator with information on his psychophysiological condition and commands for necessary measures for restoring this condition to the assigned standard.

The assigned flight program must be "concentrated" in the information model of piloted flight, the model should provide a comparison of the current flight situation with the planned one and give commands for change from one part of the program to another.

In individual cases, the information model must "remember" the preceding values of certain flight parameters, and also supply "anticipated" information, connected with a future flight situation.

One of the principal features of an information model of piloted flight, for aviation in particular, is the necessity to adapt it, so as to provide a painless transition from flying the AC by use of the models to visual flying, and vice versa. This is important, mainly in landing, as well as during takeoffs and flight in broken clouds.

By virtue of the relative danger of flight in an AC and possible breakdown of individual elements of the model, especially during long flights, one of the serious requirements on the information model was the requirement for high reliability, which is fulfilled, not only because of use of reliable technical components, guaranteeing operation of the model, but because of /81
expedient duplication of the most important components of the model for flight, as well as by way of development of technical devices having high suitability for repair.

Thus, the model of piloted flight provides the operator with information as to where and in what position the AC is, whether or not it actually corresponds to the planned flight mode and how precisely the flight program is being fulfilled, whether or not the AC control equipment is operating and what must be done and how for correction of operation of the control system. Besides, it permits timely detection of possible emergency situations in operation of the AC control system and informing the operator of the approach of dangerous or critical flight modes, i.e., the information model is necessary to the operator for orientation, guidance and monitoring in control of the AC and its systems.

In the end, during development and utilization of the information model of piloted flight, such a position must be achieved that the operator, perceiving information from the technical devices of the model, would create for himself a specific dynamic "flight image" or "image of operation of the system." However, it should be noted here that, for creation of a dynamic "image," besides processing information from the technical devices of the model, the operator must use his experience in control, his knowledge of the process being controlled and methods of action.

The idea of a dynamic "image" of the flight situation is based on the associative property, inherent in the thinking of the human operator.

As psychologists say, the dynamic "image" formed is data for making a decision on one method of action or another, which is transmitted to the AC and its systems in the form of control commands.

In the course of a flight, in the process of control of the AC and its systems, the dynamic "flight image" changes continuously and is corrected by the operator, in accordance with the actual situations and the flight program adopted. Correlations and association produced during control of a flight, are retained in the memory of the operator for use in future work as an operator.

An information model of piloted flight is composed of many technical devices, which permit coding of data in various ways, necessary to the operator for control of the AC and its systems, while putting into practice one flight program or another and of exercising control of the craft and its systems [46]. /82

The forming of an information model and its development presents considerable difficulties to designers, which depend, in particular, on the multipurpose nature of the piloted flight modelled (in the information sense) and existing technical limitations, which do not permit construction of an information model of a specific AC which is in most complete correspondence with the nature of the modelled flight or the nature of operation of the system.

Methods of Coding Information in an Aircraft

Substantiation of the medical-technical requirements for information coding methods in the model must proceed from the previously established basic position: an aircraft, with its numerous and diverse systems, is a complicated multicircuit system. For effective operation of the operator-AC system and

creation of specific conditions for the activity of the operator, who is essentially a necessary link in the overall system, providing, on the basis of his decisions, planning, rearrangement and purposeful action of the system, scientifically based methods of coding information used by the operator must be used in the AC. Information coding methods directly affect the effectiveness of action of the information transmission channel in the instrument-operator system. The paramount psychophysiological capabilities of the operator, connected with rapidity of stimulation of the information sensing organs, with speed and infallibility in reading the instruments, with the frequency of reference to the instruments during the act of controlling one changing parameter or another in the AC, on the degree of stress on the operator and reliability of his actions, as well as with the output technical characteristics of the control system, depend on these methods.

In distinction from a number of widely used monitoring systems, participating in work of which, the operator basically only evaluates the information presented to him (open systems with observers), the operator in an aircraft himself actively changes the flow of information circulating in the control circuits in necessary directions (closed systems). Under these conditions of operator actions, his psychophysiological capabilities in control depend to a great extent on the degree of processing of primary information, on the structure of the signals supplied and on the patterns of control adopted in the system. In substantiation of the most effective methods of coding information in an AC, the degree of automation of the systems he controls must be taken into account [28, 30]. /83

We must note here that, in the closed AC control systems being examined, there are interconnections and dependences between the technical characteristics of the systems, affecting the psychophysiological capabilities of the operator, on the one hand, and the psychophysiological capabilities of the operator during his work in a specific system, under specific conditions of the external medium, on the other hand. These connections, in turn, have an effect on the selection of the technical components of the system and, in particular, the information coding system.

The devices of the information model should be examined initially from the point of view of the modalities of their signals. Devices included in the information model can be divided into two main and, probably, fundamental groups, according to the modalities of the signals directed to the analyzer systems of the operator: visual and auditory (as well as their combination); as to technical devices generating signals directed to other analyzers of the operator (olfactory, temperature, tactile, taste, vestibular and pain), in practice, they are not used in information models of piloted flight of modern AC. Of course, the

conclusion should not be drawn from this that the indicated analyzers of the operator generally are not "involved" in actions for control of the AC and its systems in flight.

The overwhelming majority of the technical devices of the model are directed to the visual analyzer of the operator. These include: visual instruments (in the broad sense of the word), as well as light and color signal indicators. /84

Various acoustical devices "interact" with the auditory analyzer. Acoustical devices, built around the use of such characteristics of sound as tone pitch, rate of change in it, volume, duration, beat frequency and others, are used mainly as alarms of the onset of critical or dangerous situations in flight, as well as in various beacon systems for flight by sound according to equisignal bands.

As a rule, acoustical devices supplement visual indicators by their operation, and thereby considerably increase the effectiveness of the entire information model of controlled AC flight.

Information devices in AC can operate continuously during the entire flight or discretely, intermittently. In the latter case, systematic "interrogation" of the signals monitored can be carried out automatically or at the will of the operator. Individual information devices can operate only at specific stages (phases) of the flight.

Instruments of an information model are divided into two large groups, by the nature of their use, control and monitoring instruments. However, in certain models, information from individual instruments can be used for both monitoring the process being controlled and for control of this process.

Control and monitoring instruments can be divided into at least five groups, according to the type of information supplied. Let us examine these groups.

Measuring instruments (Fig. 1.2), indicating the instantaneous current value of one monitored or controlled parameter or another, should be pointed out first.

Fig. 1.2. Measuring instrument.

Six basic flying-navigation instruments (bank-and-pitch indicator, compass, altimeter, climb indicator, speed indicator and turn indicator), as well as many radiosystem indicators, astronomical instruments and power unit monitoring instruments, from the point of view of the information supplied by them, are the simplest gauges of the individual flight mode parameters. /85

Among the measuring instruments on spacecraft are the majority of instruments used, such as the instrument for orientation of the ship relative to the vertical point and the orbital plane, ship angular velocity meters, instruments for monitoring the cabin microclimate, "cosmic" clocks and other gauges of different parameters of controlled and regulated systems.

Measuring instruments indicate to the operator only the value of one parameter or another, leaving the entire process of evaluation, correlation and analysis of these readings as the operator's lot.

As a consequence of this, measuring instruments, in a number of cases when it is necessary to use the information of a comparatively large number of instruments and correlate their readings (especially during a time deficit), do not completely guarantee reliable and precise flying of the AC.

Nevertheless, various measuring instruments are widely used in modern aircraft, during flight when the horizon of the earth and ground reference points are not visible, and in spaceships. At present, the so-called anticipating (forecasting, predicting) instruments are beginning to be of great importance.

At high flight speeds, rapid change in the flight situation and the diversity of tasks facing the crew in flight, it becomes practically impossible in a number of cases to successfully cope with control of the AC and its systems. Under these conditions, forecasting information on a possible course of the flight and condition of the systems in the future may be of significant help to the operator.

Foreseeing the need, as a result of controlling actions, permits the operator to calculate a maneuver for control of the AC itself, as well as of one of its systems or another, precisely and in a timely manner.

An instrument which would show the altitude at which an aircraft might come out of a dive at a given flight altitude, dive angle and speed and at optimum G-force coming out of the dive could be useful in aircraft (Fig. 2.2). /86

As an example of one of the predicting instruments, which takes account of the multiplicity of interrelated factors in flight, an instrument should be pointed out, the computing device of which continuously solves the problem of the AC flight distance available at a given moment. This available distance depends on the total fuel supply and its average instantaneous consumption, the reserve fuel supply, on the true air speed and wind speed, on consumption of fuel in climbing, on the horizontal climb and descent distances and on a series of other factors.

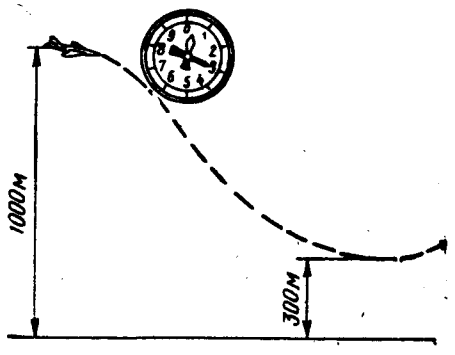

Fig. 2.2. Anticipation instrument.

Predicting instruments are particularly necessary in flight stages, accompanied by a forced rapid rate of change in the flight situation. For these purposes, an instrument can be used, which continually solves the problem of determining the landing point of the AC, taking into account possible maneuvers of it, with overloads restricted to permissible values, limiting values of the skin temperature and permissible bank angles. Control of AC descent, using such an anticipating instrument, can guarantee flight of the AC in a safe landing corridor.

In spacecraft using a ballistic descent, a navigation instrument ("Globus") is used, which makes it possible to determine the landing point of the ship at every given moment of time, if the braking rockets for leaving orbit are switched on. /87

As a rule, such instruments must have more or less complex computing devices, the operating program of which is established beforehand, or they operate in accordance with the current values of the flight parameters, determining the forecast output parameter value.

The third type of control instrument includes instruments, measuring the deviation of the parameters from their planned values ("mismatch" instruments).

Such an instrument (Fig. 3.2) consists of a sensor, measuring the current parameter value, comparator sensor and indicators. The use of instruments, which measure the mismatch in values of the derivatives of one parameter or another, is possible.

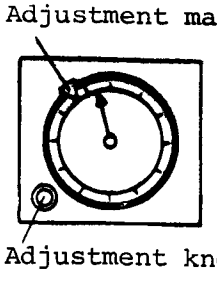

Fig. 3.2. Mismatch (deviation) instrument.

Deviation instruments can have two types of indication. In one of them, the magnitude of the deviation of the current value of the parameter from the planned one is indicated on the instrument. The task of the operator is to make the movable needle coincide with the fixed index and, thereby, execute the required program, i.e., "lining up" the present value of the parameter with the planned one. In the other type, the reading (the presence of a comparator is not required in it) is determined by one fixed scale, for example, with the aid of two moving indexes of the

current and planned values of the parameter. The task of the operator in this case is to bring these indexes into coincidence with one another. The indicator scales in both cases are graduated in units of the parameter measured.

An example of an instrument with a reading of the first type is the gyromagnetic compass indicator.

Instruments with readings of the second type are, for example, a mechanical union of a regular measuring instrument (altimeter, M meter, speed indicator, climb indicator, course indicator) with a device indicating the planned value of the parameter on the same scale, set as desired by the pilot or automatically, in accordance with the flight plan. Such instruments can be used, for example, in the process of guiding a fighter plane to an aerial target by command from earth. /88

Generally, such instruments can be used in enroute flight, in takeoff and in landing, i.e., in executing the programmed phases of atmospheric and space flight.

For instruments indicating the magnitude of the mismatch between the measured value of a parameter and the planned one, instruments with circular scales have proved to be of little use (for example, a three-needle altimeter could become a six-needle instrument, which is too complex for sensing); the digital reading also was rejected, since, with digital deviation (mismatch) instruments, the operator had to scatter his attention too much, and it was difficult for him to concentrate, to rapidly accomplish an action, dictated by the digital commands, especially in a time deficit.

Therefore, for these purposes, instruments with band scales (a scale in the form of a band moves, and the index, the cursor, is fixed) and instruments with profile scales (the indexes move in them, and the graduated scales are fixed).

Specialists confirm that readings by means of a moving band have a number of advantages over regular measuring instruments with circular scales: high resolving power, speed of reading, more precise graduation and the possibility of using nonlinear graduations.

Further, command (director) instruments should be dwelt on.[2]

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[2] Sometimes, individual authors call them "vector" instruments, having in mind that they show the direction of the operator action.

Director instruments (Fig. 4.2), actually being a synthesis of flying and navigation instruments, supply the pilot with information already in processed, correlated form, of the type "up-down," "right-left."

Comparisons of the readings of different measuring instruments by the operator are not required; he must only, for example, acting on the airplane ailerons (for departing from the flight path in the horizontal plane) and on the elevator (for departing from the flight path in the vertical plane) execute the command, the "directive," indicated on the instrument. /89

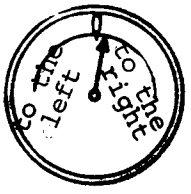

Fig. 4.2. Command (director) instrument.

The operator is freed of the necessity of carrying out complicated mathematical and logical operations and is turned into (speaking conditionally) an amplifier of the command signals of the director instrument. It is as if the operator "stops" controlling the AC and begins to "control" the needle of the director instrument. Director instruments, greatly simplifying entrance of an AC onto a planned flight path and keeping the AC on the flight path, do not eliminate the regular measuring instruments and deviation instruments, since the operator cannot judge the AC position relative to the planned one from the director instrument.

The operator, holding the command needle on zero, can be off the planned flight path: in this case, the zero reading of the needle is evidence that the aircraft is accurately approaching on the flight path.

Usually, a command instrument is made with two mutually perpendicular arrows. Holding the vertical arrow on zero provides for maintaining the planned flight path in the horizontal plane and the horizontal one, in the vertical plane.

There may be a single command index. Then, its mean position corresponds to correct execution by the operator of the command to approach the flight path, in both the vertical and the horizontal planes.

The command display can be made in the form of a system, provisionally called "interrogation-response." For example, for a command instrument determining the correct execution of a command to enter a flight path in the horizontal plane, one fixed lateral bank scale, with two independent moving indexes, the planned bank (determined by the computer) and the actual bank of the AC, can be used. The task of the operator in executing commands consists of keeping both needles coincident with one another. The display /90

discussed, in distinction from preceding ones, permits command and measurement information to be combined in one intstrument.

Experimental research on director instruments with pointer representations has shown that complete concentration on observing the pointers (cursors) of the director instrument is required in using them. However, under conditions of an acute time deficit (for example, in the landing approach m o d e), when a clear distribution of attention of the operator between the instrument panel and the ground reference points, execution of a large number of motor functions, suppression of the sense of apprehension of meeting the ground, etc., this cannot always be guaranteed.

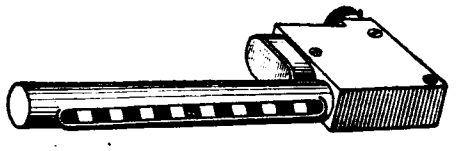

Fig. 5.2. Paravisual instrument.

For purposes of extending the attention space and facilitating its distribution during use of director instruments, the so-called paravisual director instruments (Fig. 5.2), have been developed and are being used, in the form of a system of three instruments, one in front of the pilot on the upper edge of the instrument panel (it gives the command for control of the aircraft in lateral movement) and two, located at the sides of the instrument panel (at an angle to it), give commands for longitudinal movement of the system. Each instrument is made in the form of a cylinder, with a rectangular slot, in which black and white stripes are visible. Signals are transmitted by movement of the black bands on a white background and are directed to the peripheral vision. The control task of the operator consists of stopping the movement of the black bands, in order to control the AC. Paravisual displays given additional visual information, expand the perception capabilities of the operator and have high attracting power. They can be used for monitoring autopilot operation. /91

N. D. Zavalova, V. A. Ponomarenko, Ye. Ye. Silovap and M. I. Yurovitskiy [36] have carried out research on the possibility of expanding the sensory input to the pilot (expansion of his visual perception capacity) by use of paravisual director instruments under flight conditions (Table 2).

According to the statement of the authors, the paravisual instrument has definite advantages, from the point of view of solution of additional loading problems in flight by the pilot.

And, finally, combined and integral instruments should be pointed out.

TABLE 2

Quantities evaluated	Instruments	
	Needle	Paravisual
Number of glances from the distracting object to the display (1/min)	20-30	2-10
Mean period of fixed look at the distracting object	3-5	10-20
Mean time for perceiving the distracting signal (sec)	2.42	1.92
Mean number of misses of signals transmitted at a rapid rate (%)	50	15

In connection with increasing the number of parameters monitored and the deficit of places on the instrument panel, several measuring instruments, combined in one housing, are used. Combined instruments permit, not only dealing with the area deficit on the instrument panel, but decreasing the time required for reading and perceiving the instrument readings.

This time T_k is composed of

$$T_k = \sum_{i=1}^{k} \Delta t_i n_i + \sum_{i=1}^{k} \Delta \tau_i n_i + \Delta t_3.$$

k is the number of instruments (needles, indexes and other things); n_i is the monitoring periodicity, the number of observations of the instrument (needles, indexes and other things); the value n_i decreases with increase in degree of automation of the control system; Δt_i is the time necessary for evaluation of the instrument reading; $\Delta \tau_i$ is the time necessary for glancing from one instrument to another; Δt_3 is the spontaneous distractability of the operator. /92

The values of Δt_i and $\Delta \tau_i$ are decreased by combining the instruments in one housing.

In the case of normal flight modes, the needles on the dials of combined instruments usually are placed in easily remembered configurations (cross, the letter T, inverted letter T, horizontal and vertical lines and other ways). In case of deviation of a parameter from the standard, the accustomed and easily assimilated location of the needles, naturally, is disturbed, which attracts the attention of the pilot. Combining is accomplished in the form of two-, three- and, sometimes, four-needle instruments. It has been determined that it is most advisable to combine instruments in one housing, intended for monitoring parameters which:

relate to one monitoring objective (for example, one aircraft engine);

are used together in flying or separate evolutions of it;

have a corresponding or similar value.

Two combination systems are used for monitoring engine operation. In the first of them, instruments for monitoring different parameters of one engine are combined in one instrument. These parameters usually include those for which control of the permissible limiting values is important, for example, oil pressure, fuel pressure, oil temperature. For these parameters, precision of reading is not so important during normal operation of the system. Therefore, such combined instruments usually are made with account taken of the most rapid and easy determination of deviations of the parameters from the standard from them.

In the second system, monitoring of the same parameters of different engines is combined in one instrument. These parameters usually are those for which precise setting and equalization of /93
their values for the different engines are important. These might include, for example, paired tachometers, thrust gauges of two engines and other things. The task of the operator is to "pull" one needle under the other one, and then these parameters of the different engines will be equalized.

As research has shown, the conditions for perception are not uniform for combined three-needle indicators. Readings on scales located in the upper part of the instrument are perceived considerably better than on scales having a lateral location. Therefore, in combined instruments, it is advisable to locate the indicators of the most important parameters in the upper parts.

Flight instruments are combined according to the principle of their joint use. For example, the true air speed and angle of attack meters, barometric and radio altimeters, climb indicators and the indicator of turn rate around the vertical axis, the lateral and longitudinal bank indicators with the slip indicator, heading indicator, heading angle and radio beacon station, heading,

bank, slip and turn radius indicators, or others might be placed in one housing [21, 24].

Integral instruments are a further development of director and combined instruments. The name "integral" is used here in the sense of unifying the readings of the "usual" instruments, measuring individual parameters, for the purpose of obtaining a unified, correlated picture, directly informing the operator of the flight mode. Usually, entire integral instrument systems are developed. The signals of individual sensors enter a computer, where they are processed suitably and compared with the planned values of the parameters. The output signals of the computer are delivered to the indicating instruments, by which the operator can immediately see the position his aircraft is in and what actions he must undertake for executing the planned flight plan.

The most widespread methods of coding in AC information model devices are: color, type of line, length and thickness of lines, the number of them, the shape of the symbols, their position, and orientation (Fig. 6.2 [1, 13, 43, 72]). /94

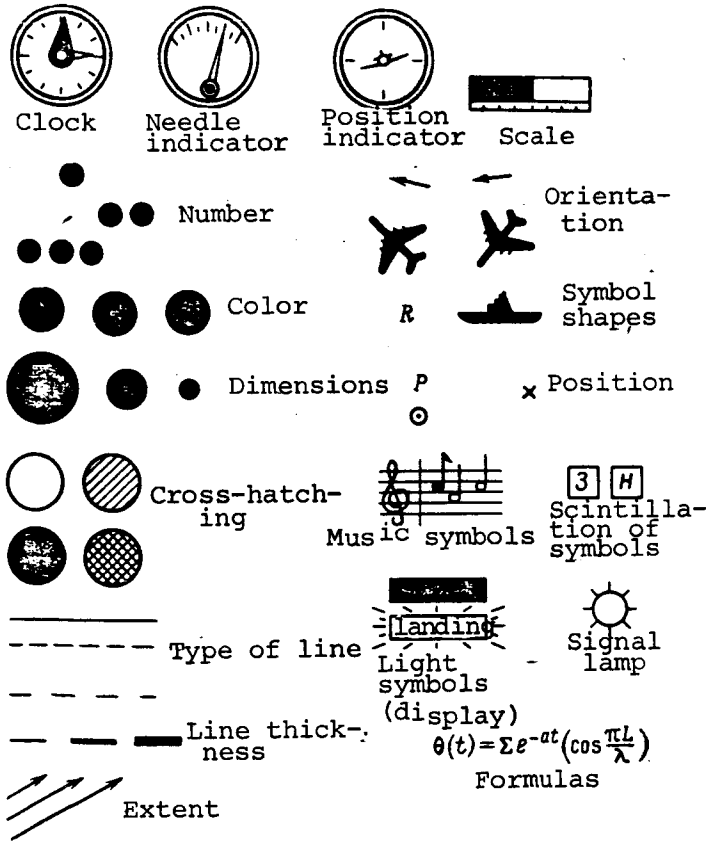

Fig. 6.2. Methods of coding information.

The number of gradations, when independent designation of each gradation is possible by various coding methods, are presented in Table 3.

The types of representation in coding information also are diverse. Scales with reading attachments, symbols, signal panels, texts, tables, bar charts, contour images, histograms, pie charts, block diagrams, graphic control panels, plann charts, graph-diagrams, functional diagrams (Fig. 7.2) and various symbols (Fig. 8.2). /95

Let us now examine the scales and counting devices of the instruments used in AC information models.

TABLE 3

Coding method	Number of gradations
Color	3-10
Size	3
Shape:	
Letter-number	50
Abstract	8-16
By association	200-1000
Arrangement:	
Linear	3-5
Two-dimensional	4-9
Three-dimensional	8-12
Orientation	4-8
Line width	2-3
Number of signals	4
Blinking or flashing frequency	2-4
Brightness	2-4
Line length	2-4
Type of line (dots, dashes)	3-4
Focusing or distortion	2
Bulk	2-3
Movement	2-10

Instruments with circular, stationary scales and rotating needles are the most widespread. The direction of rotation of the needle usually is selected so that the instrument needles rotate clockwise with increase in value of the parameter measured. Sometimes, instruments with stationary scales and moving indexes are used, but they are not widespread in AC.

Recently, in connection with the increase in number of /96
monitoring instruments in an aircraft and the restricted area of the instrument panel, the use of instruments with vertical and horizontal scales has begun. Instruments with such scales take up less space on the instrument panel. Besides, such scales are very convenient for reading certain parameters. For example, the flight altitude is read very easily on instruments with a vertical scale, and the tendency of an aircraft to decrease or increase altitude is especially well perceived. Instruments with /97
horizontal scales are very convenient for indication of the distance to the objective, flight speed and the like.

In instruments with stationary circular, horizontal and vertical scales, the length of the scale has a limited size, which

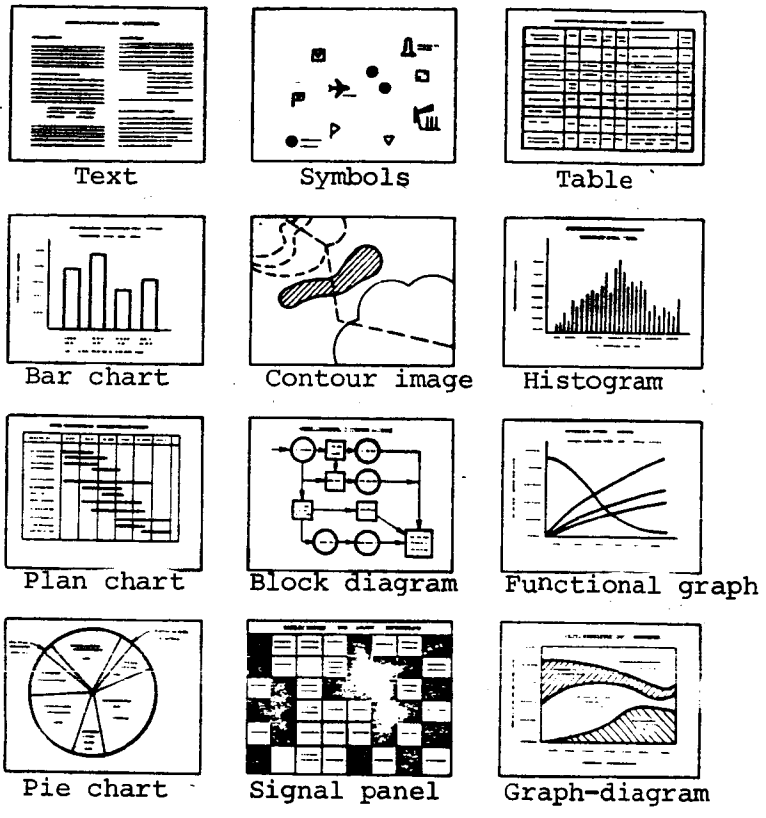

Fig. 7.2. Some types of representation in coding information.

is determined by a number of structural considerations. In measurement of parameters, the range of change of which is very wide (for example, flight altitude, flight speed, etc.), the limited size of the scale results in the accuracy of reading the parameter measured being considerably impaired. Increase in accuracy of reading can be achieved by switching the scales or by use of multi-needle instruments, instruments with moving band scales and instruments with drum counters.

Needle instruments are very convenient for observing by peripheral vision, which cannot be said of instruments with counters.

Under static conditions or for measurement of slowly changing parameters, instruments with drum counters are indispensible in aircraft.

In instruments with band scales, a scale in the form of an "endless" tape is used, the movement of which is observed in a rectangular window on the face of the instrument. The instrument itself, in this case, is considerably increased in length.

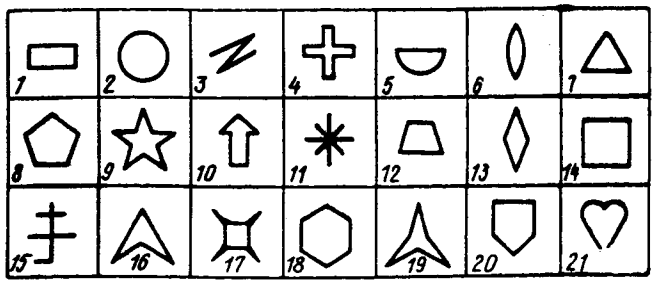

Fig. 8.2. Set of symbols highly distinguishable from one another (listed in order of ease of identification).

Concerning the scales themselves of measuring instruments, they can have both uniform numbering and division values and nonuniform ones. The greatest preference usually is given to uniform scales. However, in a number of cases, non-uniform scales are used knowingly -- damping ones (logarithmic), expanding ones /98

and others. The nature of the scale depends on the range of change in the parameters measured, the operating (primary) range of measurement and the required accuracy of measurement of the parameter at one point or another in the measurement range. For example, for a speed meter, it is more important to have a scale with smaller division values in the landing speed range and with larger division values in the remaining section of the scale. The same applies to the flight altitude indicator. Here too, a scale with different division values is desirable.

Scales are graduated either in absolute units or in percent of a maximum value of the quantity measured. Instruments with percentage scales are used or can find use for measurement of the rotation rate of the aircraft engine drive shaft, fuel supply, as well as pressure and temperature in the aircraft engine systems.

Altimeters and speed indicators with two or three needles frequently are used in aircraft, for each of which the division value on one and the same scale is different.

As experience in use and manifold research data demonstrate, multi-needle instruments, permitting the reading accuracy to increase, have one troublesome property. The percent of erroneous readings on them is significantly greater than on single-needle instruments. This is especially noticeable in those cases when the parameter measured by a multi-needle instrument changes sharply.

The results of a large number of readings, carried out by pilots from needle instruments and instruments with counters, are presented in Table 4 [72].

The percent of erroneous readings of indications from instruments with various scale configurations and structures are: for counter, 0.5%; circular scale, 10.9%; semicircular, 16.6%; horizontal, 27.5% and vertical, 35.5%. By comparison of three types of indicators, according to the potentialities of their use by the operator for solving various problems, the following qualitative results were obtained (Table 5).

Instruments with drum counters permit the scale to be lengthened, as it were. Under static conditions, with unchanged values of the parameter monitored, the accuracy of a reading from the counter is higher than from a single-needle instrument; erroneous readings under these conditions also will be less by use of an instrument with a drum counter. However, during a rapid change in the parameter measured, the number of erroneous readings increases, and it will be larger than in readings from single-needle instruments. This is explained by the fact that the pilot, using a needle instrument, has the capability of determining, not only the value of the parameter measured from it, but the trend of the

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/100

change in it (the first derivative and even the second derivative of this changing parameter). It is natural that this gives additional information on a given parameter, which cannot be obtained from a drum counter, giving factual, discrete (intermittent) information only on the value of the parameter measured.

TABLE 4 (FROM SLATE)

Parameters of readings	Regular three-needle indicator	Indicator with one needle and digital counter	Indicator with vertical band scale	Digital counter
Number of erroneous readings (%)	15,9	3,5	0.3—1.3	0.6
Number of errors of 30 m and more in reading altitude (%)	13.1	0,9	—	0.6
Number of errors of 300 m and more in reading altitude (%)	11.7	0.7	—	0,4
Mean time for comprehending reading (sec)	7.1	1,7	1.3—2.3	Less than 0.1

TABLE 5 (FROM CHAPANIS)

Task	Indicator type		
	Moving needle	Moving scale	Counter
Quantitative reading	+	+	+++
Monitoring reading	+++	—	—
Qualitative reading and tracking	+++	+	—
Setting controls	+++	+	+++

Let us dwell on one more question. It is about the fact that, in complex control systems, the operator may refer to instruments discretely, and not continually.

In use of needle instruments (or instruments with moving indexes), a larger sampling period is required than in the case of use of indicators of the digital counter type, and, in this

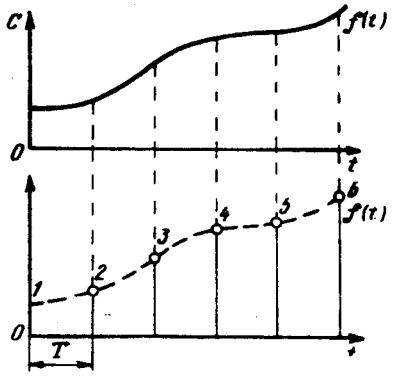

Fig. 9.2. Representation of continuous values by discrete values, f(t) - the function regulated, T - observation sampling period.

respect, needle instruments are preferable to counters. In accordance with the theorem of V. A. Kotel'nikov, which plays a fundamental role in information theory, it is known that, if a function with finite duration, observed by an operator, does not contain frequencies higher than F, it can only be determined by values of its ordinate, not in all but only at a series of points separated from one another by distances $T = 1/2F$, which are the intervals of times between discrete observations of it (Fig. 9.2).

Thus, if the operator perceives only an instantaneous value of the function observed, the discrete nature of the observation is determined unambiguously, and the time between successive observations cannot be greater or less than $T \sim 1/2F$. Less frequent observations of the instrument reading are accompanied by loss of information, and more frequent observations are a useless expenditure of time and effort for the operator. In other words, a function of finite duration t, with a limited spectrum F, is determined by $m \sim 2Ft$ on the ordinates. /101

However, the operator is capable of perceiving, not only the value of the parameter regulated itself, he can also determine the position (which corresponds to the ordinate), speed (first derivative of time) and, in a number of cases, even acceleration (second derivative of time, characterizing the rapidity of increase or decrease in rate of change of the parameter observed).

In such cases, the theorem of V. A. Kotel'nikov can be extended. When only the first derivative is added to discrete values of the function measured, for interval T, the sampling interval of observations receives a quite simple expression, in the form $T \sim 1/F$, i.e., two times larger than by observation of only the value of the function itself.

Addition of each succeeding derivative permits the time interval between discrete values to be increased to the value $T = (K + 1)/2F$, where K is the order of the higher derivative, when all lower order derivatives are observed for each discrete value. Besides, period T is a discretely increasing function of the number of derivatives observed. Thus, if the operator determines only the amplitude and second derivative of the parameter measured, the sampling period of observation remains equal to $1/F \sim T$.

It should be kept in mind that the theorem of V. A. Kotel'nikov gives an adequate, but not necessary, number of readings; for periodic functions with period T_n and duration t, for example, it is sufficient to take only $\frac{2tF}{T_n} + 1$ independent numbers [21, 24].

In this manner, the sampling interval for reference to the instruments or monitoring periodicity in the control process should be in conformance with the frequency of change in the parameter regulated, which is measured by this instrument. This must be taken into account in development of AC control systems for various operating conditions. /102

If, for example, the monitoring periodicity of the aircraft longitudinal movement parameters are unchanged and greater than the frequency of the long-period oscillations, with increase in flight speed, errors in the angle of inclination of the flight path increase in proportion to the speed, but errors in altitude, in proportion to the square of the speed; deviations of flight speed remain almost constant and increase only with increase in thrust-weight ratio.

If, as actually happens, the monitoring periodicity decreases approximately in inverse proportion to the flight speed, remaining greater than the frequency of the long-period oscillations, errors in angle of inclination of the flight path increase approximately in proportion to the square of the speed, and in height, to the fourth power of the speed.

In such control systems, instruments permitting the monitoring periodicity of the flight parameters indicated to be increased should be used.

Actual data [33] show that, in actual flight, there is considerable variability in periodicity of the gaze fixation time of pilots, necessary for reading the flying-navigational instruments in monitoring the flight modes. The mean gaze fixation time on instruments (according to the results of movie photography):

Bank and turn indicator, 0.45 sec; altimeter, 0.52 sec; climb indicator, 0.52 sec; speed indicator, 0.64 sec; compass, 0.62 sec.

During slow flow of the processes of control of individual systems in an AC ("excess" time for the operator) and the necessity for continuous observation of the monitored parameters during periodic (or cyclic) change in them (for example, change in the pitch angle during high speed AC flight at low altitudes), it is advisable to use information systems with specific output signal structures. Monitoring systems with delivery of signals to the operator on the value of the parameter measured and the first and

second derivatives of this parameter can be used most successfully.

A symbolic display on cathode ray tubes (CRT) is used mainly /103
in ground air traffic control points for rapid and operational representation of an air situation from one or several radars at definite points. In the research of N. I. Boyko, S. G. Darevskiy, Ye.S. Zav'yalov and others [3], it was established that readings from CRT scales, in comparison with the scales of regular needle instruments, are considered to be 20% faster and of higher accuracy by the operator in a number of cases. Speed and accuracy of identification of numbers and symbols, for example, in numerical displays, depend on their shape (Fig. 10.2), brightness, spatial arrangement, as well as illumination [56, 59].

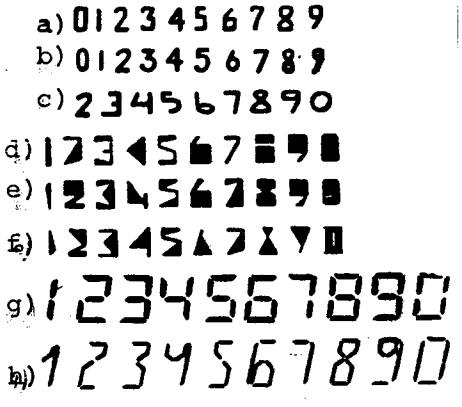

Fig. 10.2. Basic types of number outlines: a. From Berger; b. from Macworth; c. from Slate; d. from Lansdale; e, f. modification of Lansdale figures; g, h. On modern electroluminescent displays.

The Macworth type is considered the best of the number outlines of the normal type. Numbers composed of straight lines (Berger type) are identified with still greater accuracy. The Slate type, despite the unusual form, is identified best of all under conditions of difficult perception.

A graphic display is an economical method of transmission of information, in the form of diagrams, charts, and ciphers. They permit almost any measurable quantities to be transmitted, as well as directly observable relationships between them in a three-dimensional scheme, accessible to visual perception. A graphic image is not a representation in the real sense of the word, since the properties of objects and processes are not reproduced in them. Here, the information is transmitted to the operator in the form of an unusual "three-dimensional code." Three-dimensional coding is a specific means of transmission of information, distinct from other types of coding, and it is transmitted in the form of symbols. Geometric figures, in the properties of which the nature of the processes depicted are only conditionally reproduced, serve as signals of one characteristic or another of the processes. In addition, the method of perception of the three-dimensional code has much in common with perception of an image. In processing the information, the man operates by well-known three-dimensional images. In this case, the possibility appears of solution of complex mathematical problems at the level of descriptive thinking. /104

Graphic control panels, which, in distinction from regular instruments, are more descriptive, also are a promising type of display. Graphic control panels should give a graphic representation of the flow of a process and warn the operator of the possibility of complications in one component or another of the process controlled (for example, signals of automatic systems operations, entry of a craft into the dense layers of the atmosphere and exit from them; indication of radiation dose and rate; and others).

Measuring instrument display devices in AC can be divided into two main groups, by nature of the display:

with symbolic (conventional) displays;

with graphic (pictorial, visual) displays, including visual flight analogs.

All needle instruments, in which the needle moves, symbolizing a change taking place in the object or in some parameter or other of the object measured by this instrument, are examples of measuring instruments with conventional displays. The common characteristic of instruments with symbolic displays can be given as follows: /105 the readings of these instruments are far from perfect; symbolic instruments require rearrangement of the reflexes of the operator. For more or less successful use of such instruments, long training of the operator and repeated training for maintaining qualifications are necessary.

Historically, the development of AC instruments went basically in the direction of development of conventional methods of display.

An ideal instrument with graphic display would be an instrument in the form of a model, reproducing the pictures visually observable from a flying AC.

Turn and bank indicators and heading measurers ("planned" instruments) in aircraft are examples of instruments with a relatively graphic display.

Reproduction of two display principles is possible in instruments:

view towards the AC from earth (observer on earth) and

view from AC to earth (observer in AC).

The difference here is that, in the first case, the needle, circle, line or marker of any other geometric shape, indicating (symbolizing) the AC position (any changing AC parameter), is movable, and the index relative to which the reading of this

changing parameter is made is stationary, connected to the instrument housing. In the second case, on the other hand, the index symbolizing the changing parameter is stationary and the reference index is movable. An instrument of the first reading system "tells" the operator where it is, but does not "say" what must be done. In instruments of the second type, the stationary index symbolizes the AC, and the movable element of the instrument, the earth. In this case, in order to bring the AC to a planned position, the AC must be maneuvered in the direction of the deflection of the movable index of the instrument.

Other display systems are logically identical, and they can be mastered well by the operator during training. Consequently, both systems are widely used in onboard instruments. There is no ground for contrasting one type of display with another. Arguments for and against the "on the AC" and the "from the AC" principles counterbalance one another to a considerable extent. Thus, for example, in examining monitoring of the AC heading, the following arguments can be introduced, which contradict one another. If the AC, in the process of turning to the right, changes its heading, its former heading and the corresponding flight direction appears after a left turn. And, from this point of view, it would appear advisable to have a stationary AC silhouette as the indicator and a moving heading scale symbolizing the stationary ground reference points. On the other hand, the object controlled by the operator is the AC, reacting to the action of the operator through the control surfaces. To the operator in an aircraft there are fixed connections: right pedal forward, stick to the right, and the aircraft turns to the right. /107

Therefore, the operator expects the movement of the heading indicator on the instrument corresponding to that of the AC. From these considerations, a stationary heading scale with a moving indicator turns out to be preferable.

Thus, if evaluation of the heading indicator is approached with the question "where is the AC turning?" the preference will be for the "view towards AC from earth" principle. If the question is asked "what is the point of the compass?" the preference changes to the "view from AC to earth" principle.

The image presented by certain bank-and-pitch indicators sometimes does not correspond to what the pilot observes, when he wishes to determine the position of his aircraft relative to the horizon. In visual flight, when the aircraft begins to climb, the pilot sees the horizon apparently going under the nose of the aircraft, and in diving, he notices that the horizon rises. It appears to the pilot that the aircraft does not move relative to the stationary horizon, but that the horizon moves relative to the aircraft. A bank-and-pitch indicator can give an image of movement of a miniature aircraft relative to a stationary horizon,

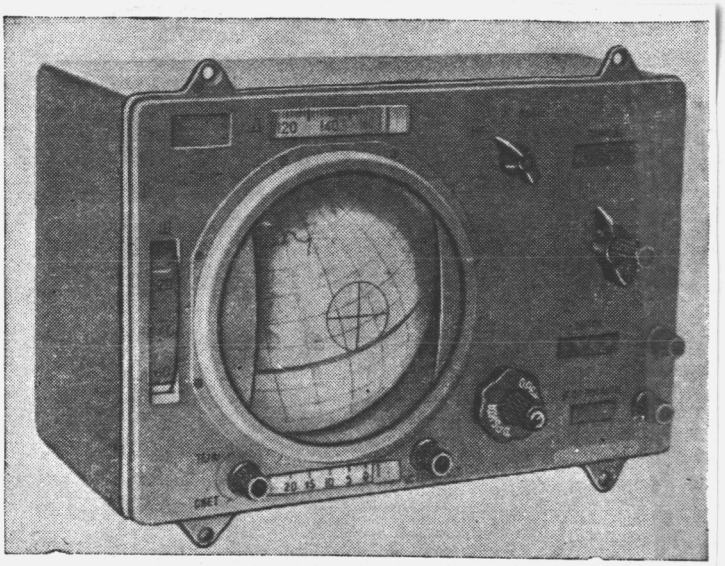

Fig. 11.2. Indicator of spacecraft position relative to ground reference points.

or a moving horizon line moves in the opposite direction relative to the stationary image of the aircraft.

Development of a display system must proceed from the fact that the basic purpose of an instrument informing the pilot of the aircraft position relative to the plane of the horizon is to create a precise mental concept of the situation. In thise case, to give the pilot a pseudovisual concept is completely optional. How this mental concept is produced is not important, provided the process of perception is easy and the result accurate and unambiguous. /108

Bank-and-pitch indicator readings are easily perceived, but they are not always accurate and unambiguous. Therefore, the bank-and-pitch indicator is not always appropriate to its purpose.

Efforts to reproduce visual orientation conditions in a bank-and-pitch indicator have psychological limits, since it is not natural for man to make a measurement of the angle and its apex.

Therefore, at high pitch angles, for example, during a climb at an angle of 60°, the pilot does not always feel confident in orienting on the bank-and-pitch indicator. A logical conclusion is to change to an instrument indicating pitch angles, as though measured during observation from the side. Such a proposal goes contrary to the demands of the adherents of image display, who consider that the instrument readings must simulate the picture observed by the pilot through the cockpit visor, which assists him in changing from blind flight to visual orientation (for example, when breaking through cloud cover). Otherwise, supposedly, the danger of confusing the pilot arises upon an unexpected exit from the clouds. However, if the pilot has a complete mental picture of the position of his aircraft, there is no confusion, since there will be no contradiction at all in the presentation. The pitch angle indicator needle rotates through 360°, owing to which, the pilot can determine his position relative to the horizon at any moment when executing a loop. At high angles of attack

(i.e., at low speeds), the aircraft can lose altitude, although the instrument will indicate a positive pitch angle. A climb indicator, located next to the pitch indicator, is used to monitor this mode. The climb indicator can even be used for correction of the pitch angle indicator gyroscope, similar to the way in which a gyro compass is corrected by the terrestrial magnetic field sensor. Then, the pitch angle indicator readings will give true angles of inclination of the flight path and will not totally depend on the angle of attack. Since, in the majority of cases, flight takes place within a pitch angle range of ±30°, the instrument scale can be made logarithmic, providing increased reading accuracy at small pitch angles (for example, in landing approach by instruments). /109

In a number of cases, the so-called curtain is used for representing the bank and pitch angles in the bank-and-pitch indicator. In place of the usual aircraft silhouette, the position of the bank-and-pitch indicator line is represented in this instrument: the black sector designates the earth and the white, the sky. When the aircraft changes position relative to the lateral axis, the ratio between the white and black sectors changes correspondingly. For example, when the aircraft gains altitude, the white sector becomes larger than the black one.

Pilots for the most part approve instruments built on the "observer on the earth" principle, and navigators, on the "observer in the AC" principle.

Of course, the essential question is the degree of descriptiveness which should be introduced into the instrument readings. It is completely obvious that visual flight, giving the pilot a sensation of safety, actually does not provide for obtaining the total data necessary for control of the aircraft. Besides the fact that a visual impression cannot accurately judge a number of flight parameters, for example, altitude and air speed, random interference in the information channel, owing to change in the landscape, can lead to dangerous consequences. This becomes particularly clear if low altitude flight at very high speed, when the earth rushes under the aircraft with such speed that the pilot does not succeed in distinguishing reference points or in comprehending information received from them, is examined. It is clear that, under such conditions, it is much more convenient to use an instrument in which simplification and arbitrariness, in comparison with the visible picture of the terrain flown over, is introduced, assisting in orientation.

Therefore, in development of methods of descriptive displays, the effort must be made to provide the pilot with conditions of perception of ground reference points to which he is accustomed, but without the accompanying interference and inaccuracy of actual visual flight. /110

However, a number of objections can be presented against descriptive display methods. In particular, it can be assumed that a completely descriptive display is not only technically impossible, but that, in general, it is practically impossible to provide a reproduction of a three-dimensional picture on a two-dimensional scale, and that an unsuccessful effort at descriptive presentation of flight parameters is more fraught with dangerous consequences than any arbitrary method of displaying them.

Analogs of visual flight can be executed in the form of a single set of instruments, giving indications of all flying-navigation parameters, or in the form of two separate instruments, supplying flight and navigation parameters separately.

Television is considered to be a more nearly ideal analog of visual flight. In it, the basic information is delivered to the surfaces of two small hemispheres. A grid is applied to one of them and the second hemisphere is smooth. If a portion of the hemisphere is shown with the aid of the television camera, a picture similar to that observed by the pilot during flight over a flat field is reproduced on the cathode ray tube screen, broken into square sections. A network of lines, converging at a point on the horizon, will be seen on the display screen (Fig 12.2). Changes in heading and pitch are achieved by movement of the spheres with respect to the stationary cathode ray tube [22, 29].

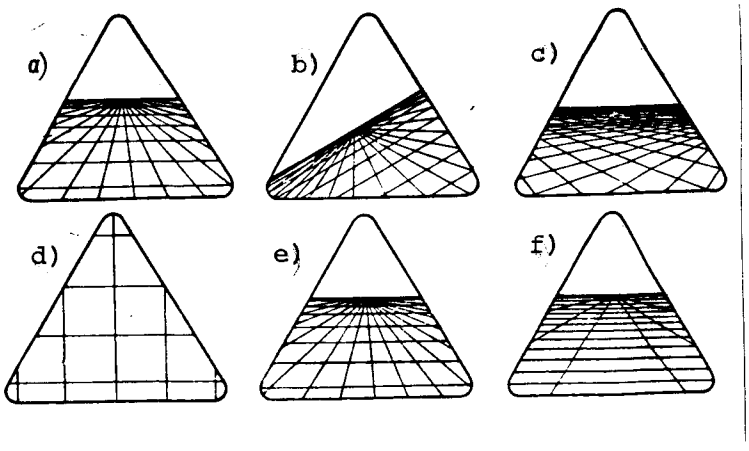

Fig. 12.2. Aircraft position display on cathode ray tube screen: a. horizontal flight on planned heading; b. right bank; c. horizontal flight at an angle to the planned heading; d. vertical dive; e. flight at high altitude; f. flight at low altitude.

In a number of cases, a simulation of the flight path is given on the television screen of the flight display, the analog of visual flight, in addition to the usual network of lines, which is a representation of the surface of the earth. This is achieved by means of a device in the form of the so-called "road in the sky."

Such a display improves the quality of pilot orientation during instrument flight. When the aircraft is banking, the entire image is inclined. The change in heading causes a shift in the image. A change in pitch changes the perspective. A /111

change in altitude in horizontal flight is represented by expansion of the texture gradient (the distances between the parallel lines). Presentation of the flight speed is created by the impression of forward movement of the observer. Thus, in horizontal flight on a planned heading, the horizontal lines appear to emerge on the horizon, continuously move and disappear under the lower edge of the display. It is natural that this dynamic process cannot be presented in a stationary illustration.

The field of the observer, delineated by a network of lines, is very similar to the picture which the pilot might see when flying over a terrain broken into square sections.

A picture of the terrain flown over is represented on the television navigation display, and data on the flight distance and duration is supplied as well [21].

Electron optical flight-navigation displays are known, which give a visual integral presentation of the flight parameters. It is intended for installation in high speed aircraft, having a limited field of view. /112

On the large screen of the display, the pilot can see a color image of the terrain, produced by visual, radar and infrared means, navigation parameters and data on takeoff and landing.

The main component of the indicator is a modified optical sight, used on aircraft for visual observation of the surface of the earth and coverage of space in the forward hemisphere of the aircraft.

The pilot can select and see one piece of data or another on the display, corresponding to a given flight phase. Producing information from various sources on one display, it is not necessary for the pilot to look at different instruments, which requires eye accommodation each time.

By means of such a display, the flight mode can be monitored by superimposition on the visible image of takeoff strip markers, indicating the distance to the takeoff point or run termination; information can be accumulated on the three-dimensional position of the aircraft on the visible image of the earth or airspace ahead of the aircraft, with simultaneous indication of the angle of attack and airspeed on the edge of the display; a visual or radar image of the terrain, image of the aerial navigation chart or a combination of these images, etc., can be selected during enroute flight.

In a landing approach and during landing, the positions of the course and glide path beacon beams are represented

graphically and are superimposed on the picture of the visual situation, with indication of the angle of attack and speed at the edge of the display.

One variety of the pictorial display system also is a system using contact analogs ("Conalog") (Fig. 13.2). This system creates the effect of direct presence. On the screen of this system, the pilot-astronaut can see a constant conventional image of the situation, as if he observed it from his command post. The system operates on a real time scale, simulating "contact" control by means of the visual image. Under conditions of high G-forces, visual perception of the pilots-astronauts can be disturbed, their actions will be constrained and they will not be able to observe all the instruments. At this time, the "Conalog" system makes it possible to replace the entire group of regular monitoring instruments by one device [29]. /113

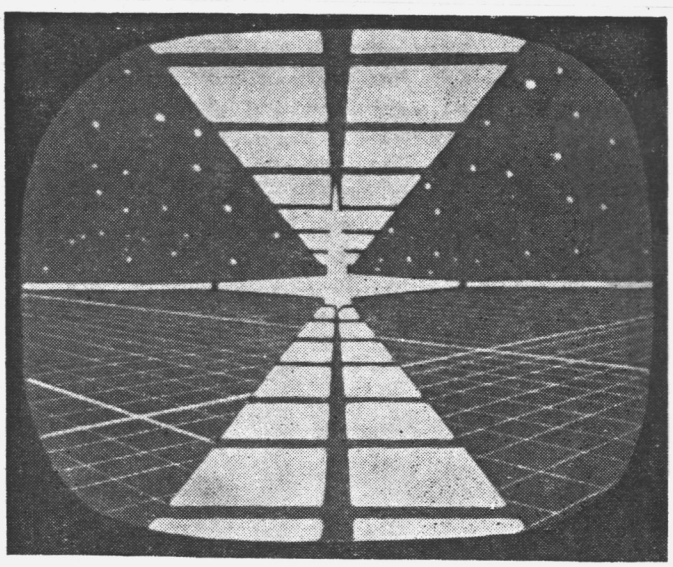

Fig. 13.2. Contact analog of visual flight ("Conalog").

Combination of the image of actual reality with artificial constructions in a single screen becomes exceptionally important in space, especially when a spacecraft is at a great distance from the planet or other heavenly body towards which it is directed. A real television image of the planet becomes interesting only when hovering over it and, in this case, it is scanned distinctly on the entire screen.

The method of combination of actual and artificially formed images proves to be especially useful during landings of spacecraft on the moon and during the return to earth. The pilot-astronaut, looking at the screen of the apparatus, sees, not only the object he is approaching, but signals assisting him in orienting himself in space. In addition to the fact that this instrument assists astronauts in landing, it facilitates reliable control of the craft in flight, since images showing what action is required of the astronaut in certain unforeseen cases will be indicated on the screen. /114

Inasmuch as the image on the contact analog apparatus is created by a standard television scan, any other information which can be obtained with the aid of television can be reproduced on

its screen. This permits its use for display, for example, of parts of the craft itself which are inaccessible to direct view, and for receiving information transmitted from ground television stations.

If there is a periscope on the craft for observation of the outside world, the contact analog apparatus becomes a very important instrument, since it permits the astronaut to adapt his vision to space conditions more rapidly.

The sharp increase in duration of aircraft flights and transfer of crew activities in a number of aircraft to low altitudes above the earth aggravates the execution of tasks in efficient flight control and monitoring the space ahead of the AC. One of the possible methods of increasing the quality of monitoring the external situation in flight is the use of a system with a panoramic display (television units with a computer) on the AC. Such systems permit navigation data and other information on the course of the flight to be obtained and accumulated, the necessary control signals for changing the flight heading and data on approach to designated reference points and other things to be shaped [29].

In connection with the increase in flight speed, to guarantee faster perception of information by the pilot (as has been established, with every hour, a flight at high speed requires 3-6 times more measurements than during flight at low speed), the significant acceleration in processing of data, precise control under difficult flight conditions (during change from instrument flight to visual flight and vice versa, during distraction of the operator's attention to the execution of other tasks, when he is fatigued, during prolonged monitoring of automatic onboard systems and other things), the use of new types of displays of flight parameters is required in the AC information model. Display systems, constructed on the principle of "inspection ahead" or "looks ahead," are being used for these purposes [22, 23, 29]. In this system, the bank-and-pitch indicator readings, director indicators, data on the basic flight parameters (altitude, aircraft position, deviation from the glide path, flight speed, and other things) are projected on the front window panel of the cabin. The pilot sees a symbolic representation, in the form of parallel lines, circles and dots. This method of presentation of information can be used for increasing the accuracy of flight along the flight path and in visual flight, as well as for monitoring autopilot operation. /115

Control will consist of holding a flight path indicator (dot) in the center of the circle simulating the aircraft.

U. Woodson and D. Conver [13] report on the utilization of a new type of descriptive display (the "Kinalog" instrument), in

which an aircraft maneuver is represented by changing types of displays, initially "from the outside in," and then gradually changes and transfers to the "from the inside out" type.

In the opinion of the authors, the singular feature of this type of display is the effort to correlate the display with the aircraft maneuver as the pilot himself perceives it (Fig. 14.2).

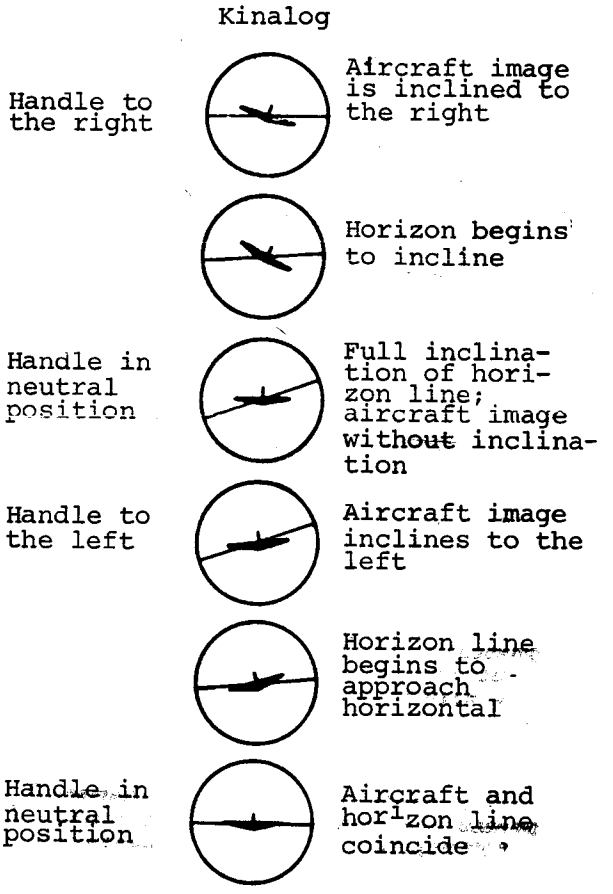

Fig. 14.2. Visual flight display ("Kinalog," from U. Woodson and D. Conver).

Signal indicators are used in AC, together with instruments. The greater part of them are luminous and, sometimes, of the acoustical type. Signal indicators can be: attractive (if the signal lamp lights up near the instrument or panel of the unit monitored); warning (when a signal appears, with an indication as to precisely what the trouble is); guidance (if the signal directs the operator to a specific group of instruments or a specific lever); notification, if the signal has sufficient content as to the event taking place (for example, "no fuel"). Signal indicators also can be command ones (for example, "lower landing gear," "reduce gas," etc.).

Light signal indicators are distinguished by color. The most widely used color code is that for transmission of dangerous flight mode or emergency situation signals, in one control system or another. Red signal indicators warn of danger; if the danger is accompanied by an emergency situation, a red, intermittent, "blinking" signal indicator is used. A yellow signal indicator is "advisory," and a green signal indicator records normal condition of the object or normal flow of the process. /117

Light signal indicators usually are combined in groups and are located in special panels on the instrument panel. However, experiments have shown that, by furnishing 5-6 signals on one signal panel, the attractive effect of the remaining signals drops.

The "burning" of an emergency or especially important signal on the background of any other signals may cause a delayed reaction by the operator. Therefore, in constructing signal systems in AC with a large number of signal indicators, it is advisable to install them in separate signal panels, according to function.

Acoustical signal indicators can be the sources of sound of a constant pitch (sirens) or of changing tone. For example, during aircraft let down, in dangerous altitude signal indicators, below the danger level, the pitch of the acoustical signal is decreased and when exceeding the altitude, the pitch is increased. The acoustical form of data transmission is suitable, as a rule, in situations where the necessity for transmission of a limited amount of information, as well as when the visual analyzer of the operator either is heavily overloaded or is functioning unsatisfactorily.

Due to their attractive influence, the effectiveness of signal indicators is very high. To improve the effectiveness and reliability of signal indicator systems, the attractive properties of the signals must be reinforced. In particular, to improve the attractive power of emergency and warning signals, they should be made intermittent at the beginning of their period of action, with a change to continual burning after the operator responds. It is advisable to back up all signals requiring immediate action with acoustical signals. All critical parameters should be signaled by light or acoustical signals.

Signaling with changing color illumination, depending on the situation created, deserves attention, as well as light signaling with musical accompaniment. Signal indications of these types /118
can facilitate the creation of an emotional background which is most favorable for carrying out the work of the crew (mainly under conditions of prolonged space flight).

Color also frequently serves for designation of items in an AC, belonging to one group of systems or another, for marking critical points on instrument scales and for information as to whether or not systems or individual components of them are operating. In all the cases enumerated in this section, color signals are used for monitoring readings. Meanwhile, proceeding from the great color discrimination capabilities of an operator, it can be expected that color coding will prove to be effective in those cases where a qualitative reading of indicators is required. For example, it is expedient to use a change in degree of saturation of a color signal for transmitting information on the direction of change in the processes regulated.

In this manner, color, used as an alphabet of signals, can be a highly effective type of data coding. It should be noted that, in development of a color code, the mechanisms of color vision and

the conditions under which they are brought about must be taken into consideration.

AC Instrument Panel as an Example of an Information Model and Medical-Technical Requirements for its Grouping

The cockpit equipment of a modern AC is so numerous and complicated that the necessity has developed for regulating its placement, considering the purpose of the AC and the features of the human body.

Experience shows that variants in location of instruments on the panel can be almost as numerous as there are pilots participating in elaboration of this problem.

If the instrument placement is convenient for one flight mode, it may prove to be inconvenient for another mode. Therefore, some primary mode must be selected.

Sometimes, "mode importance" coefficients are introduced. For example, for a two-engine, high-altitude jet fighter plane, the primary purpose of which is the conduct of aerial combat, /119 the entire flight is divided into several modes.

Determining the frequency and order of use of instruments by pilots in these flight modes, in the long run, requirements for efficient placement of the instruments on the panel are successfully worked out.

A similar development can be carried out for spacecraft.

The habits of flight personnel and the desire to have instruments "for all cases" in the cockpit, for monitoring a series of secondary parameters frequently does not permit correct solution of problems in shaping instrument panels.

In a number of cases, in view of the complexity of solution of the tasks of standard placement of all instruments on instrument panels of aircraft leads to the conception of standardizing the location of only six basic instruments, namely: speed indicator, altimeter, bank-and-pitch indicator, compass, climb indicator and turn indicator or glide path zone deviation indicator.

In new foreign standards, establishment of a T-shaped arrangement of the main instruments (there are four here) has been proposed. In this instrument placement scheme, different groups of associated flight data should be systematized and the instruments should be located on the panels, regardless of the type and form of data (Fig. 15.2). At present, it is considered advisable to provide a distance on the order of 0.6 m between the primary instruments on the control panel and the operator's eyes.

The center and left zones of the instrument panel stand out as the most accessible for observation, in placement of these instruments on the panel. In this case, a rapid transition from instrument flight to visual flight also is provided, in particular, during landing after coming out of the clouds. The right part of the instrument panel, as a rule, is separated out for placement of aircraft engine monitoring instruments. The effort is made to place monitoring instruments in such a manner that, during normal engine operation, the needles of all monitoring instruments are located horizontally (in the 9 or 3 o'clock positions).

The lower part of the instrument panel is allotted to instruments monitoring the auxiliary aircraft systems. /120

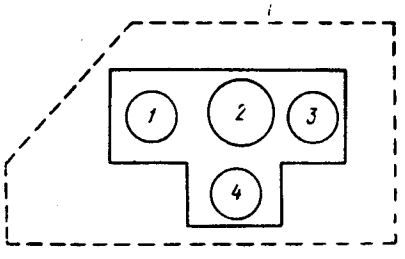

Fig. 15.2. Diagram of T-shaped location of main flying-navigation instruments: 1. primary instrument-airspeed indicator, supplementary -- M-meter and angle of attack indicator; 2. director bank-and-pitch indicator or regular bank-and-pitch indicator; 3. primary instrument -- altimeter, supplementary -- climb indicator and true altitude indicator; 4. navigation indicator.

Ways of adapting information systems to effective stimulation of the analyzers, rapid and accurate processing of information and, consequently, higher quality execution of control tasks in an aircraft and in a spacecraft have, not only similarities, but differences. Space flight, by its characteristics, has a sharply delimited phase (stage) nature. Here, in distinction from aviation flight, its individual phases (stages), for example, flight in orbit, can proceed for an extremely long time, but approach to orbit and descent from it to earth take place in a relatively short time. The nature of space flight makes it mandatory that the astronaut obtain information from all or a majority of instruments simultaneously; on the other hand, a fully specified group of instruments and controls must be used at each stage. Obviously, the "darkening" of individual groups of instruments, not used by the astronauts in a given flight stage (for example, "darkening" during prolonged orbital flight of instruments used for descent of the craft, or docking instruments after execution of this flight stage and others) is advisable.

The idea of "curtaining" groups of instruments on spacecraft can be put into practice relatively easily, by use of indicators in the form of cathode ray tubes with switching of the primary data sensors from a special flight program device, and it increases /121 the reliability of AC control systems with operator participation.

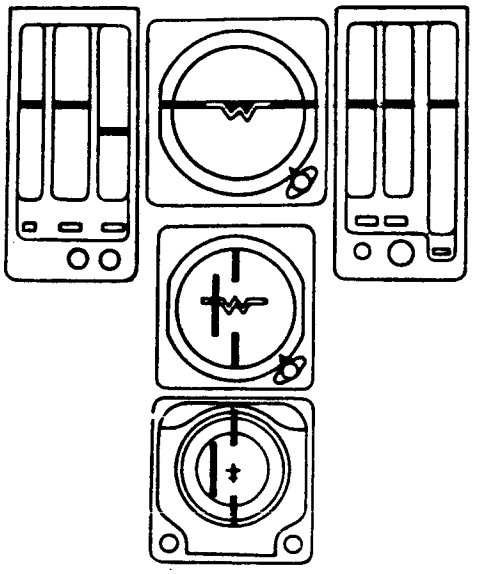

Fig. 16.2. Arrangement of navigation instruments on the instrument panel (according to the "look down" and "look ahead" principle).

The effort to simplify and ease the task of the pilot in observation and control of the flight mode parameters has led, as we have seen, to substitution of many normal onboard instruments by new, integral instruments. Integral instruments change the general appearance of the instrument panel in a radical way. This panel permits presentation of well-defined command data to the pilot, with logical movement of the aircraft controls. It gives the pilot horizontal and vertical reference lines, corresponding to the "look ahead" and "look down" (Fig. 16.2) [29].

The flight mode parameters corresponding to the "look ahead" along the horizontal reference line, are regulated by "forward-backward" movements of the aircraft control stick, and they include the pitch angle, airspeed and M number, vertical speed, altitude, angle of attack and acceleration. Parameters corresponding to the "look down" along the vertical reference line, are regulated by lateral deflections of the stick and include heading, bank angle, turn rate, navigational and tactical information. /122

In this manner, it can be determined whether or not the flight mode corresponds to the planned parameters (indicated by the command indexes) or the required spatial position of the aircraft and the entire navigation situation, by glancing at the horizontal and vertical lines.

An aircraft map position indicator also can be used in the equipment set. At a high flight speed, the pilot does not have time enough to scan the map of the terrain flown over. Besides, in the cramped cabin, it is difficult to work with regular aviation charts, and there is no place to store them. Two methods of aircraft position display are possible.

1. With an optical projection system, in which a small part of a small-scale map is projected in color from a glass slide onto a screen 18-25 cm in diameter. The slide is moved relative to the objective by means of a tracking system. There can be different magnifications for taking in larger or smaller sections of the terrain. An image of a small aircraft and a grid of

parallel lines, which are oriented automatically according to the aircraft heading, are superimposed on the map projection. Movement of the map relative to the small aircraft is accomplished by signals from the automatic navigation machine, in conformance with the actual aircraft route.

2. With a television system where the map initially is projected on a screen by a television camera, and then on a cathode ray tube in the pilot's cabin. In this case, the aircraft position indicator on the map can coincide with the radar indicator. An advantage of this system is the possibility of having the projection apparatus outside the cabin. Among the shortcomings of this map image system are high weight and the black-and-white image.

Power plant monitoring instruments are subdivided into three groups:

engine instruments ("percentage" thrust and rpm indicators, exhaust gas thermometer, oil manometer and jet nozzle flap position indicator); /123

cruising mode monitoring instruments (indicating the optimum altitude and M number values for the maximum flight distance and duration modes);

fuel system instruments.

It is desirable to indicate to the pilot the actual parameters of the engine in comparison with their optimum values, which change themselves, depending on the flight mode, by means of the engine monitoring instruments. For this purpose, instruments with profile scales, on which moving arrows show the actual values of the parameters, are used. At the same time, the scales themselves move automtically, determining the optimum values according to the engine modes of operation.

When all five engine operation mode parameters reach the assigned values, the instrument needles, installed in a row, occupy a position in one horizontal line. Deviation of any of the needles from this line immediately indicates disturbance of the assigned mode to the pilot. Signals of the assigned modes are generated by computers.

Less accurate instruments, with circular scales ("percentage" thrust and rpm indicators and exhaust gas thermometer) are placed beneath the instruments with rectangular scales. They serve to inform the pilot of the trend of change in these parameters and for duplication of the more precise instruments when they get out of order.

Cruising mode monitoring instruments, together with the calculators of optimum altitude and M number values, providing the maximum flight distance to be obtained, are located on the instrument panel, under the first group of instruments (Fig. 17.2).

An AC instrument panel is completed by introduction of light signal panels, with a previously compiled standard text, into the AC cockpit. By means of this display, in the normal course of the flight, its progress can be demonstrated, and, in case of failure, the emergency system is indicated and pilot action is prompted. /125

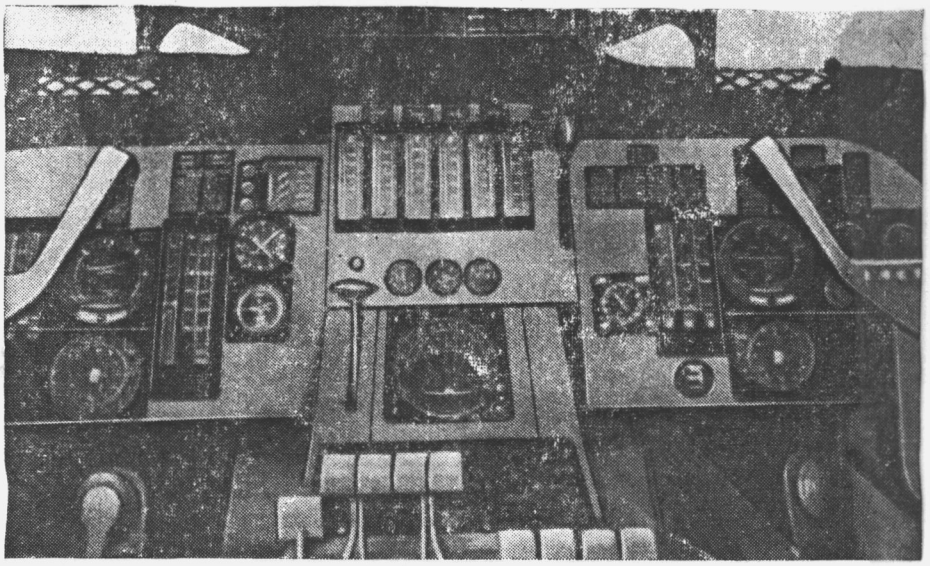

Fig. 17.2. Instrument panel of modern passenger aircraft: center -- three-dimensional flight indicators; on sides -- combined flight-landing approach instruments; above -- paravisual instruments.

A photograph of a mock-up of an instrument panel intended for single-place aircraft is given in Fig. 18.2.

Unification of the separate panels for separate systems and apparatus into single control panels is of great importance for improving instrument panels [22, 23].

Manual Controls in an AC as a Component Part of the Information Model and General Medical-Technical Requirements Placed on Them

After the operator makes a decision, the final stage of the control-execution cycle of operator actions begins. In the

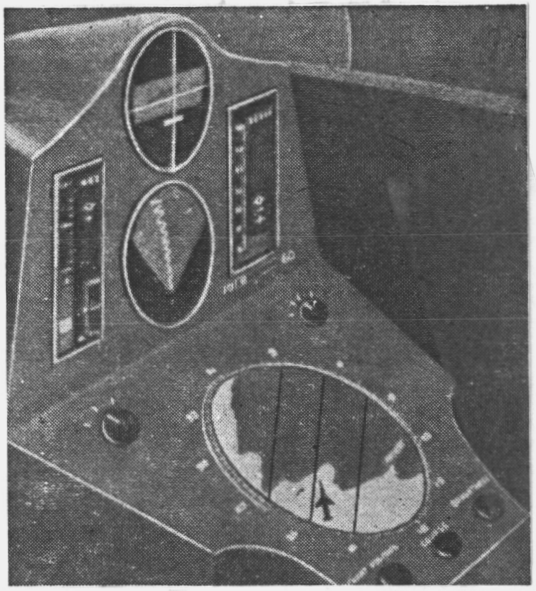

Fig. 18.2. Mock-up of instrument panel of single-place aircraft.

majority of cases, the operator executes motor reactions: he pushes buttons or moves levers, switches on or switches off apparatus. Although the movements in themselves are comparatively simple, the complexity of all final control actions turns on their regulation by the central nervous system. /126

The operator output "signals" necessary for operation of a control system on an AC, as a rule, are created by contracting or elongating the muscles, and they are applied in the form of a force on the controls. As has already been pointed out, the forces created by the muscles of the back and legs can reach hundreds of kilograms briefly, and the force of the arms, 40 kg.

The main controls in an aircraft are the control stick (column), pedals and throttle. In addition, there still is a large number of buttons, switches, "star knobs" and other controls in aircraft. Controls of both the aircraft type and specific ones are used in spaceships.

Reactions of the controls to a force applied by the operator will differ, depending on the dynamic properties of the control. If, for example, the control stick on which the force acts is flexibly connected to stationary components, its movement will be proportional to the force applied. If the control stick is connected through a damper to stationary components, its movement will be proportional to the integral of the force applied. Finally, with inertial connection of the control, its movement will be proportional to the second integral of the force applied.

It should be noted that, with the "emergence" of the operator as a "link" in the control system, information is transmitted through the kinesthetic receptors to the central nervous system, which signals the degree of activity of the effector organ muscles. This property is similar to feedback; therefore, it has received the name of kinesthetic feedback. If it were not for this feedback, the link under discussion would have integrating properties.

One of the important requirements for controls included in a control system with operator participation is that the direction /127

of movement of the control be in conformance with the direction of displacement of the moving index on the instrument monitoring the change in the parameter controlled by the given unit.

Efficiency of operator activities depends to a great extent on compatability of the direction of displacement of the indicating device and movement of the control. It is known from data in the literature that the causes of 17% of the pilot errors in the USA are that they incorrectly interpret the direction of movement of the indicating device. This is particularly noticeable when the operator is working with both hands, at high speed and in a stress situation [1, 13, 43, 72].

It has been established by numerous experiments that the following memory rules should be made:

During movement of the controls forward, to the right, upward, away from oneself, the instrument indexes should be displaced clockwise, from left to right, from the bottom up;

During movement of the levers backwards, to the left, downward, towards oneself, the indexes should be displaced counterclockwise, from right to left, from the top downward.

In this connection, the results of the comparative effectiveness of various movements of the controls in response to movement of the measurement index must be introduced (Table 6).

TABLE 6 (FROM MITCHELL)

Relation between movement of control and index	Mean number of errors in 60 trials	
	Action with one hand	Action with two hands
Control upward -- index upward	3.0	4.2
Control forward (away from self) -- index upward	4.5	5.3
Control to the right-to the left -- index upward	7.0	9.0
Control back (to self) -- index upward	6.8	11.1
Control downward -- index upward	8.0	11.9

Simultaneous control of the AC in which the pilot is located and control of another object from this AC leads to the necessity for investigation of the most effective memory rules for the operator for these cases, in connection with the direction of

movement of the controls to movement of moving indexes in the information coding system. The choice of this rule is of special importance for flight stages in which extreme conditions act on the operator (weightlessness, overload, hypodynamia).

Investigation of this problem has shown that, from the point of view of the psychophysiological stresses on the operator, speed of developing his skill and accuracy in executing control tasks under similar circumstances, it is less advisable to use the rule used by pilots ("the object of control follows the handle"). It is better to put another memory rule into practice: "the image on the indicator follows the control stick." /128

The number of controls and actions with them should not exceed a minimum, determined by the composition and purpose of one system or another.

The system of controls should be organized so that their joint use guarantees, not only execution of the task, but convenience in manipulation, taking account of the logic of the motor paths of the operator -- the relative significance, frequency and sequence of operations with them, their roles in critical situations, as well as a number of other factors such, for example, as the functional asymmetry of the arms (the presence of a stronger right and weaker left arm), etc.

The controls should be easily identified and distinguished by means of definite external indicators, for example, such as shape, size, location, color, etc. Errors in identification of controls frequently become the cause of accidents. Thus, in the American AF, during World War II, errors in identification of only two controls in one of the types of combat aircraft caused 400 accidents in 22 months. As a result, American psychologists worked out a set of handles for control sticks, which were easily identifiable by shape. It is considered desirable that the shape of the controls have a meaning, i.e., suggest their function: /129 for example, the aircraft landing gear lowering lever should be made in the shape of a wheel, the flap controls, in the shape of a wing, etc.

It is true that this requirement is not always fully put into practice in modern AC.

Some aircraft control sticks and the most diverse shapes of regulating (control) handles, existing and recommended by specialists, are presented in Figs. 19.2 and 20.2.

Controls should be built and located in such a manner that the necessary effect can be realized in one specific way. If there are no special reasons for it, alternative methods of executing operations should be avoided. Optimum efficiency in use

of controls for specific purposes should be provided, taking account of their sizes, shapes, proportions, movements and sensations of pressure caused.

The number of "human" errors in the man-machine system must be reduced to the minimum. And for this, the selection, construction and placement of controls should respond to the psychophysiological and anatomical characteristics of man. It is bad if, for example, the fingers slip from the buttons.

That is why the most convenient shapes of buttons are rectangular with rounded corners and rectangular with rounded upper edges. It also is recommended that the distance between neighboring buttons be no less than 5 mm and between groups of buttons, 20 cm.

The effort for pressing frequently used buttons should be equal to 140-600 gf, and from 600 to 1200 gf for rarely used and most crucial buttons. Vertical arrangement of the buttons is more favorable than horizontal, from the point of view of speed of action and their distinguishability [59].

The features of the medium in which they are set and, in particular, the working position itself, have a decisive effect on the working efficiency of the operator. Such factors as temperature, G-force and others deserve exceptional attention in this connection. Aircraft autopilot control should be decided on. This control is carried out by three methods: /131

from the autopilot control panel, by turning the pitch, heading and turn potentiometer knobs;

through a control stick, which is a block of control signal generators, connected with handles of various shapes;

through a single aircraft control stick.

In transmission of a control stick signal by any method with a drive mechanism amplifier, a position signal is taken off and a coordinating mechanism is switched on, so that, beginning from the moment of termination of transmission of the control stick signal, the aircraft mode is stabilized. In a majority of cases, the control stick signals are transmitted as aircraft angular velocities. Turns of the dials on the panel or deflection of the control stick causes the appearance of an aircraft angular velocity which is proportional to this deflection. In control by autopilot, through a single stick, the control stick signal also is transmitted as aircraft angular velocity, which is proportional to the force applied to the control stick by the pilot, /132 in this case. Therefore, manual control to the autopilot by a single stick over a wide range of speeds, differs from normal

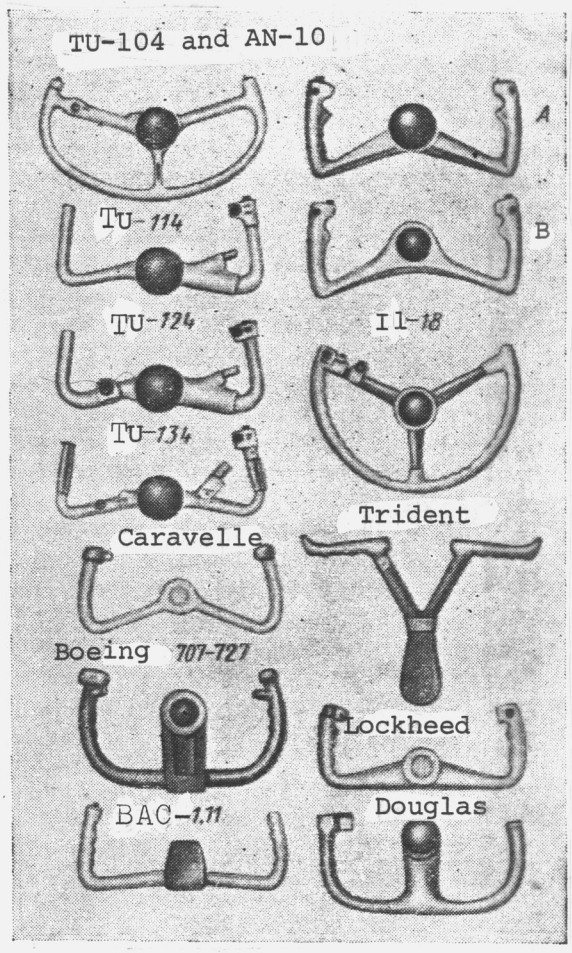

Fig. 19.2. Shapes of control sticks of some domestic and foreign aircraft (A, B - control sticks, the shapes of which, in the opinions of specialists, most fully correspond to practical expediency and contemporary requirements of engineering esthetics).

controls and, in the latest models of autopilots, the control panel again is becoming of primary importance.

The methods of manual control of an aircraft through the autopilot cannot be considered established, since tests in use of single angular velocity control sticks cannot be considered completely successful.

Let us now examine several common features of operator-control stick interactions. It seems at first glance as though that control would be best, by use of which almost no resistance has to be overcome. However, in this case, the operator does not "feel" it and, therefore, acts with insufficient precision. Some increase in resistance leads to increase in precision of control. Therefore, the resistance (as well as the shape and size) of the control must be calculated, with the characteristics of not only the motor, but the sensory apparatus, of the arms (or legs) or the operator taken into account. It must be remembered here, particularly, that after introduction of booster control to aircraft, removing the load from the control stick and pedals, special control stick and pedal loading mechanisms were introduced, to make up for the lost "sense of control."

Thus, manual controls, requiring perception of the counter-pressure of components of the object of control, should be planned with the critical sensitivity of the operator to various magnitudes of force taken into account.

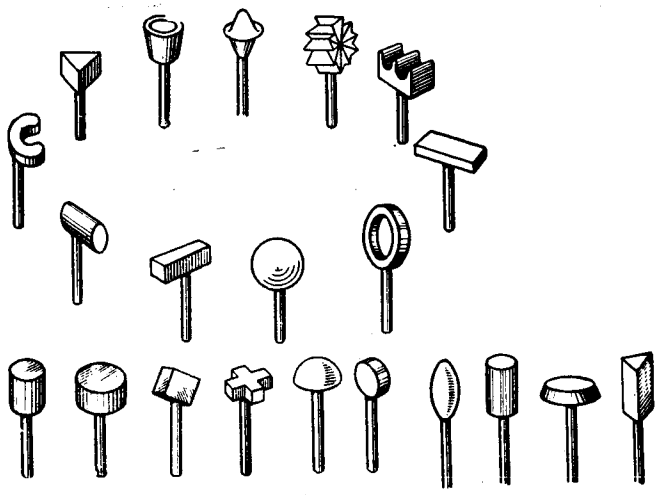

Fig. 20.2. The most widespread control stick handle (button) shapes.

At a pressure of less than 2.5 kgf, pressure perception sensitivity in the operator is reduced, i.e., a high distinguishability of pressure magnitudes is necessary, and, at pressures of more than 4 kgf, it becomes practically constant and equal to 0.06. In this manner, with a 20 kgf force on the stick or pedal, the sensation of change in resistance will equal 1.2 kgf (20 x 0.06). It has been determined experimentally that it is inadvisable to permit a decrease in the force applied to manual controls below 2.5 kgf, and to foot control pedals, below 4-5 kgf, since, otherwise, the operator cannot provide the necessary precision and definiteness in his control of the system. He cannot achieve smooth pressure and tremor (shaking) will appear in his actions. /133

The ratio of the magnitude of movement of the control stick to the magnitude of movement of the index in the control instrument has a great effect on the quality of manual control by the system and, principally, on the primary adjustment time. The primary adjustment time is decreased with increase in the distance traveled by the control index at each turn of the controlling mechanism. The time for most precise adjustment, however, is increased with increase in displacement of the index per single turn of the knob. The optimum turns out to be at a ratio of displacement of the index per turn of the knob of 1:1.5. This ratio is optimum if precise setting is required. If precision of the final adjustment is not so important, then it is proper to increase this ratio, so that the required position can be achieved more quickly with coarser tolerances. In the latter case, a 6:1 ratio is the optimum. In using right-left deflection levers (for example, for control of the position of theindex on the linear scale of an instrument), the optimum transmission ratio -- movement of the index with respect to the movement of the end of the lever -- will be from 0.25 to 1.3. For control adjustment levers, the optimum is a transmission ratio of 2.5:1.

Placement of the operator controls must be strictly based on anthropometric data on man, with account taken of artistic-design requirements as to AC cabin color and design [13, 43, 72].

CHAPTER III. FLIGHT CONTROL IN A TIME DEFICIT /134

Beginning with the first steps in development of aerial movement, pilots began to run into a shortage of time in executing a flight program. The time deficit accompanies a crew essentially at all stages of a flight. This is felt especially during takeoff and landing of aircraft, in execution of missions -- guiding an aircraft towards high-speed aerial targets and during flights at low altitudes.

The effect of time deficit will show up heavily in the future, with the continuously expanding requirements for regularity and all weather aircraft flights, increase in precision in executing missions and increase in reliability of aerial transport.

The activity of a pilot in flight control systems, including faultless, highly precise actions in countering disturbances, selection and tracking reactions using the information model of flight, analysis of the situation and making decisions, has become extremely complicated. The limited psychophysiological capabilities of man have begun to show up now. With training alone, no matter how perfect and long it might have been, it has become impossible to guarantee effective operation of a pilot in these stages. A radical change in the technical components of control systems, with which the pilot interacts in flight, and the creation of fundamentally new control systems and information model components was demanded.

The landing approach, execution of the landing and touchdown is the most difficult stage of flight. It is accompanied by a forced rapid pace of change in the flight situation, and the /135 execution of diverse, complicated and precise movements and operations by the pilot, under conditions of an acute time deficit.

Therefore, it was not accidental that, as is pointed out in foreign press data, up to 40% of the total number of aircraft disasters take place at present during the landing approach and landing. During the landing approach and execution of the landing, the time for completion of which is counted only in minutes overall, the pilot uses essentially the entire set of flight-navigation instruments, observes ground reference points, executes a series of actions to maneuver the aircraft in the vertical and horizontal directions, changes and maintains the values of the flight-navigation parameters according to a specified program (which can change, depending on the specific circumstances), carries out diverse calculations (including determination of the lead angle for compensation of drift, the point of contact with earth, etc.), carries out communications with the flight controller, lowers the landing gear and carries out other work.

Landing characteristics of modern aircraft, which "require" precise actions of the pilot and that he operate with maximum care, must be considered. We point out here the fact that aircraft landing speeds nevertheless tend toward some increase, and that the motion characteristics of some aircraft in banking are disadvantageous for the pilot and that the aircraft are especially sensitive to even a small movement of the control away from the pilot (a greater increase in their vertical speed).

For purposes of easing execution of operations by the pilot and increasing reliability, two approaches to the creation of landing systems are being examined at the present time.

1. Creation of automatic systems, with only the functions of monitoring the proper operation of equipment left to the pilot (this direction is being followed in England).

The logic of this approach depends on the following:

In 1965, an average of one flight accident per million landings took place in the world (according to some sources, 1.5 million). Therefore, in order to sharply reduce the number of such accidents, the goal was set to have no more than one failure per 10^7 landings, which means a six-fold increase over the reliability level of existing landing systems. Therefore, in England the unique way was selected, in their opinions, the way of total automation of landings, using multichannel systems, with two- and three-fold redundancy of equipment, reciprocal control and the possibility of switching off this system in the event of failure. /136

2. Creation of instrument landing systems with pilot participation and the use of graphic displays, giving the same volume of information as in direct visual observation (display on the side window or on an intermediate screen).

Specialists in the USA do not consider the solution of the problem of all-weather landings is possible only by means of total automation, and they are oriented towards improved display systems and visual guiding, with the pilot maintaining his active place in the control circuit.

Pilots also divide on this point of view, and they prefer to complete an aircraft landing independently, not trusting this operation entirely to an automatic machine, since, all the same, accomplishment of the landing remains for them in the event of failure of the automatic machine.

It should not be forgotten that, with failure of an automatic machine, the nature of the pilot activity changes suddenly. From a relatively passive checker, he must practically instantaneously

change into an active manager, who must act under tension to restore the disturbed flight mode.

At present, according to reports in the press, instrument landings of aircraft are possible at a cloud height of 30 m.

The majority of air transport companies in the USA, England, France, Federal Republic of Germany, and other countries resolved in 1972 to reduce the meteorological minimum during landing to the level of category III, in conformance with the characteristics of the category conditions of the meteorological minimums established in 1962 by the World Civil Aviation Organization (Table 7).

TABLE 7. METEOROLOGICAL MINIMUM CONDITION CATEGORY CHARACTERISTICS

Category number	Cloud height, m	Visibility along runway, m	Means of provision
I	60	800-600	Ground instrument landing system, with improved instruments, improved runway light system
II	45-30	480-360	Horizontal field of vision equipment; equipment of runways with markers visible in any weather; duplication of glide path receivers and autopilots; automatic engine thrust control system; improved altimeter for recording overshoot altitude (30 m) and failure prevention equipment
III A	0	210	Improved instrument landing system ground equipment; new on-board equipment; automatic leveling off and drift correction system computers; automatic engine thrust control and monitoring systems
III B	0	45	
III C	0	0	

There are various opinions and approaches abroad towards creation of landing systems. Specialists in France and the USA, jointly developing the AWLS all-weather landing system for aircraft of the Caravelle type, note in an official document that the automatic levelling off mode should not be used in the presence of /137

passengers onboard and that the autopilot must be switched off at an altitude of 15 m. But some pilots consider even an altitude of 30 m dangerous for making a decision to complete the landing or depart for a second try. In fact, breaking through the cloud cover at an altitude of 30 m, the pilot has available 13-15 sec of time in all (depending on the rate of descent, usually equal to approximately 2 m/sec) to align the aircraft, kill the speed, correct for drift and touch down. If it is considered that each "interaction" of the pilot with the instruments "takes away" about 3 sec from it, he practically cannot use the instruments during the landing. /138

Thus, the change to landing under category III (and especially IIIC) conditions requires a radical reexamination of the entire system of instruments and their indications. Here, it might be a question of creation of automatic landing systems, which must accomplish letdown, touchdown, landing run and taxiing along the runway, simultaneously providing the pilot with the necessary information on the operation of the equipment and the course of the landing and touchdown. In case of failure of the automatic system, reserve systems (including the manual control circuit) must be cut in sufficiently rapidly that the maneuver being accomplished can be dependably completed or stopped.

In the USA, three methods of aircraft control during levelling off and landing are used:

According to a previously assigned landing flight path (programmed control), in which the control system reduces the mismatch between the actual and programmed aircraft positions to zero;

At the assigned touchdown point, at which the system either maintains the aircraft on the calculated flight path or compiles a new optimum flight path, in order to accomplish the aircraft landing at the assigned point on the runway;

By an exponential pattern, in which the vertical speed of the aircraft during landing is proportional to the actual flight altitude.

These methods differ from one another in complexity, weight and size of equipment, in providing accuracy of landing (especially during the action of disturbing factors), reliability and convenience of control by man. In particular, the first two methods can provide landing of the aircraft at an assigned point in the presence of disturbances; however, with programmed control, in the event of insufficiently successful choice of regulation pattern and with considerable changes in the dynamic characteristics of the aircraft, elimination of the dispersion may have an oscillatory nature and lead to a rough landing. With the exponential

pattern, any change in altitude (vertical wind gusts, for example) leads to a change in the location of the touchdown point relative to the calculated one.

The difference in landing control systems, by degree of participation of their pilots, their structure and control patterns adopted, are evidence of the choice of compromise solutions, taking account of the results of engineering psychology research on the capabilities of the operator to control the aircraft under conditions of a sharp time deficit. /139

It is most likely that the most nearly correct approach to provision of aircraft landings under conditions of poor visibility is the approach in which the completely automatic landing and landing with active participation of the pilot are not opposed, but are reasonably combined. As engineering-psychological research shows, the use of a semiautomatic landing system for stabilization of the aircraft center of gravity on the landing approach and during letdown is of especially great importance.

The task of stabilization of the aircraft center of gravity on a strict three-dimensional flight path, by separate instruments, is considerably more difficult for the pilot than the task of stabilization of the angular position of the aircraft relative to the surface of the earth. On the basis of data coming in from the different flight measurement instruments, the pilot cannot quickly make a decision on the nature and degree of action on the controls to stabilize the aircraft on the flight path. A number of flying instruments, such as, for example, an indicator of the deviation of the aircraft from the glide path leg, permits the pilot to determine on what side his aircraft is relative to the objective or the assigned flight path and to visualize where the aircraft center of gravity must be changed, in order to approach the flight path or the objective. However, the instrument does not indicate how to do this in the optimum manner, and the pilot solves the problem himself, which requires great effort under these conditions. In this case, the quality of execution of the flight stage is reduced and, sometimes, especially during a time deficit, on the whole, task execution can be disrupted.

A diagram of an aircraft flight by blind landing instruments (BLI) in a course beacon zone is presented in Fig. 1.3. The flight path by this instrument is considerably different from the optimum. Using the BLI, which gives a zero reading only at the moment of intersecting the assigned flight path, the pilot is practically unable to accomplish a high-quality landing, i.e., carry it out precisely on the assigned flight path. /140

A diagram of the aircraft manual control circuits, applicable to flight along an assigned landing flight path is presented in Fig. 2.3. The abundance of instruments, the forced rapid tempo

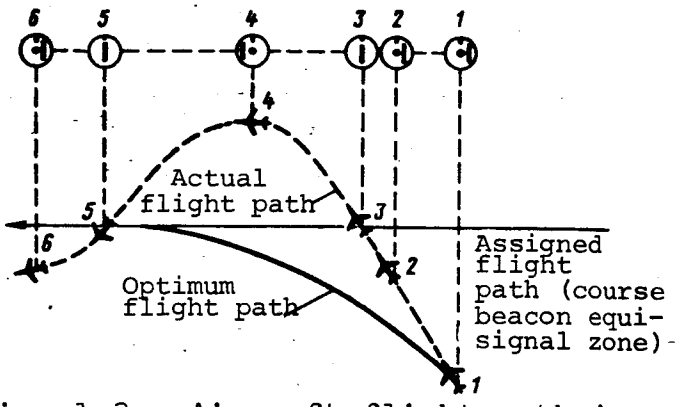

Fig. 1.3. Aircraft flight path in the horizontal plane using BLI in a course beacon zone.

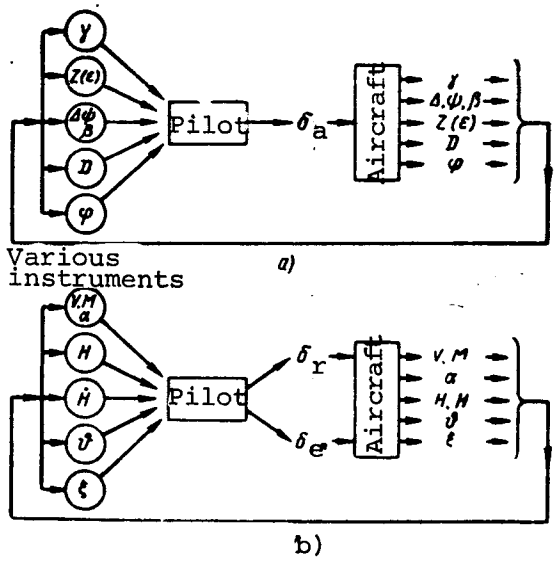

Fig. 2.3. Nonautomatic aircraft control circuit: a. in lateral motion;(ϕ - radio station heading angle, D-distance to radio station, z(ε) - lateral deviation of aircraft from assigned flight path in linear (and angular) units, $\Delta\psi = \psi_{back} - \psi$ - difference between assigned and current aircraft headings, β - slip angle, γ - bank angle, δ_a - aileron deflection angle); b. in longitudinal motion (ξ - deviation of aircraft from assigned flight path in vertical plane, δ_r and δ_e - deflection angles of rudder and elevators).

of the control process, the restricted nature of the psychophysiological capabilities of the pilot all cause trouble in carrying out a flight along an assigned flight path.

In landing, the pilot runs up against simultaneous distribution of his attention over several instruments or several groups of instruments. During flight on the last leg, the pilot's main attention is concentrated on the readings of the compass, bank-and-pitch indicator, speed indicator, altimeter and other instruments. If account is also taken here of the work connected with lowering the flaps, switching on the landing lights and other things, the great load of attention on the pilot in carrying out the flight component under discussion becomes obvious.

Before touchdown, the pilot, in order not to cause undesirable lateral loads on the landing gear, must deploy the aircraft (by means of an intentionally established bank or by means of a flat turn), so that its longitudinal axis is directed parallel to the runway axis.

The complexity of aircraft control for the pilot, during flight on an assigned flight path in landing (just as during flights along assigned flight paths in carrying out other flight stages), /141

is that, in the course of a flight, by action on one aircraft control surface or another, as a rule, the readings of, not one, but several monitoring and control instruments at once are changed, since the group of parameters monitored by these instruments are interconnected through the objects of control (the aircraft).

To simplify the work of the pilot-operator during flight along an assigned flight path, together with different measuring instruments, it is advisable to use a special command instrument, the control needle pattern of which must be designed in an appropriate manner, on the basis of information received from different instruments. By this command instrument, the pilot can much more simply approach the assigned flight path (Fig. 3.3) and guide the aircraft along this flight path, by holding the instrument needle on the zero graduation. This instrument, automatically, without participation of the pilot, determines the magnitude and direction of the necessary action on the aircraft. /142

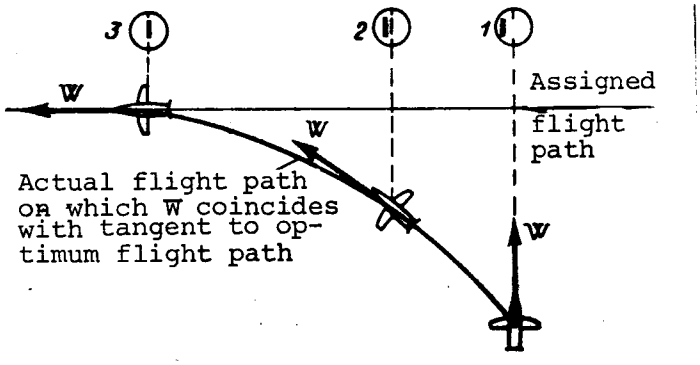

Fig. 3.3. Diagram of approach of an aircraft to an assigned flight path, using command flight-navigation instrument.

The concept of the command instrument is as follows: deflecting the control surfaces, the pilot changes the magnitude and direction of the aerodynamic moments acting on the aircraft, as a result of which the aerodynamic forces applied to it change.

The results of research in flight trainers show that, in bringing an aircraft in for a landing by separate instruments, with initial aircraft deviations from the heading of 30° and of 3° from the equisignal band of the landing course beacon, the operator (pilot), for a period of 75 sec, cannot bring the aircraft into the equisignal zone with the necessary accuracy, even with great overexertion. The use of a director (command) instrument in these cases permits the pilot, without special effort, to bring the aircraft into the equisignal band in an optimum manner within 15 sec (Fig. 4.3).

In recent years, as was pointed out in the preceding chapter, new means of obtaining information during landing under complicated meteorological conditions have appeared, giving an image on the front window of the pilot's cabin. In this case, a projection of the optical image of the situation in the field of view of the /143

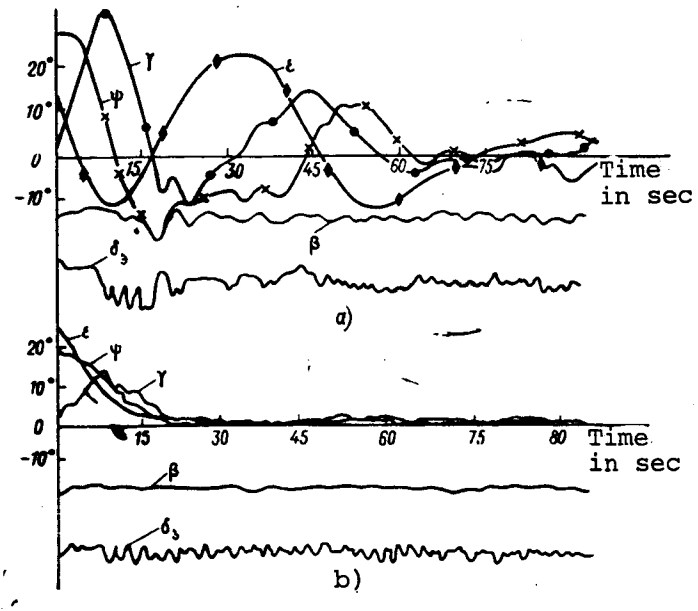

Fig. 4.3. Change in aircraft flight parameters when coming in for a landing: a - by separate instruments (inital conditions: $\psi = 30°$, $\varepsilon = 3°$); b - using command instrument (initial conditions: $\psi = 30°$, $\varepsilon = 2.5°$).

pilot, focused at infinity, is provided on the window. Visibility of the image is maintained day and night, over a wide range of change in background brightness. In this case, as a rule, there is no parallax between the projected and actual pictures. The use of image collimation frees the pilot from the necessity of systematically adapting the eye when looking from the projection display to the external situation, and it permits the position of the image relative to the picture of the external situation to be fixed, regardless of the position of the pilot's head.

Components of the image on the lateral window and a schematic diagram of the placement of display apparatus in the cabin are presented in Fig. 5.3. /144

It is desirable to provide continuous prediction of the touchdown point in the landing parameter display. Data on flight conditions and on the dynamic characteristics of the aircraft and flight control system can be used for this. Prediction of the touchdown point should be indicated by a separate indicator on the runway surface in the admissible touchdown zone. The shape and position of this zone are calculated from the landing speed, the values of errors, the flight line and from data on the runway condition.

Foreign specialists have come to the conclusion that, at present, during flights at low altitudes, it is simpler to control the aircraft with the pilot included in the control system, than with the aid of a completely automatic system.

It is only required that special preparation and training of pilots be provided and that new components of the information model of flight be developed.

Let us examine in general outline the basic features of the operator-AC system during flights at low altitudes. /145

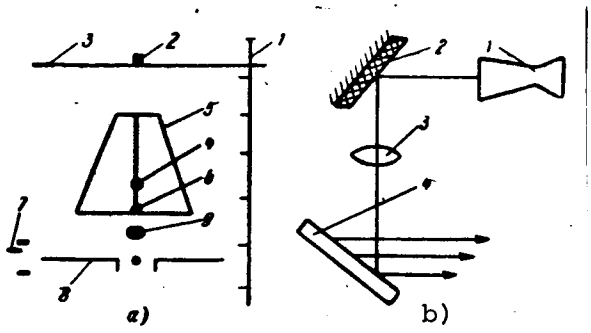

Fig. 5.3. Schematic diagram of image on lateral window: a - elements of image on lateral window: 1. altitude scale, 2. heading index, 3. horizon line, 4. deflection marker, 5. runway image, 6. aiming point, 7. airspeed index, 8. flight path index, 9. director marker; b - diagram of display apparatus placement in the cabin: 1. image generator, 2. mirror, 3. collimating lens, 4. semireflector.

The main one of them is that this entire flight stage takes place essentially under conditions of a sharp time deficit for the pilot-operator, and this superimposes specific impressions on his psychophysiological capabilities and the nature of the compatibility of the logical operations in data processing with the motor acts of the operator [57]. The time deficit depends mainly on a considerable increase in rate of movement of the aircraft relative to the surface of the earth, and this leads to the fact that the "time budget" of the pilot for carrying out navigation calculations, for corrections of the flight path, in accordance with the assigned plan, and for observation of objects on the earth, proves to be considerably less than during high-altitude flights (although it is not so great here).

Besides, the necessity for "extraction" of part of the time in finding and recognizing objects and in finding and overcoming possible obstacles in the path to the objective decreases the time for interaction of the pilot with the control and monitoring instruments.

The time deficit is accompanied by an extremely elevated stress on the pilot, dependent on: nearness of the earth (the probability of collision with obstacles is increased); small altitude reserve for executing a necessary maneuver, in particular, when failures and breakdowns in the aircraft systems arise; the danger of missing ground reference points needed for executing the flight mission; grounds for appearance of spontaneous movements of the controls (especially away from the pilot), with the very high efficiency of the control surfaces in the dense atmosphere; the expectation of aircraft bumping, caused by vertical near-surface air currents (especially in mountainous terrain and at dry land-water boundaries); the necessity for executing the flight mission with complex types of maneuvers. The importance of individual instruments for the pilot in such a flight can differ from their "weight" during flights in the stratosphere, for example. Thus, the pilot begins to give more attention to the climb indicator and vertical G-force indicator, etc.

In flight at low altitude, the pilot turns his head considerably more often, alternately sensing instrument data and turning to the space outside the cabin; under certain conditions, this can facilitate the development of a harmful effect on the pilot's body of G-forces caused by Coriolis acceleration. /146

P. K. Isakov, D. I. Ivanov, I. G. Popov, N. M. Rudniy, P. P. Saksonov, and Ye. M. Yuganov [47] show that an experienced pilot spends about 5% of the time on reference points outside the cabin during flight at high altitudes, and, in flights at low altitudes, the ratio between observation of reference points outside the cabin and monitoring the instruments becomes approximately one.

Scientific grounding and purposeful training of pilots significantly increases the effectiveness of solution of ground landmark recognition problems in strictly determined time intervals during flights at low altitudes.

As experimental work has shown, the pilot can be provided with specific information by the radar display (cathode ray tube, picture storage tube with visible image). However, the best solution of "adjustment" of the flight information model to the operator is given by use of "projection" displays, with instruction indicators directly on the lateral window, according to the principle of those which are successfully used in landing under complex meteorological conditions. Such a display does not attract the attention of the pilot to the instrument panel, and the image on the lateral window can be produced so that it does not interfere with perception of ground landmarks. Concerning the features of pilot training for low altitude flights, a number of authors consider it advisable to train the pilots for determination of the G-forces only with the aid of muscular feelings. In this case, the pilot will not read the G-force indicator readings and be distracted from observation of landmarks. According to the data of some investigators, pilots, after training, determine G-forces with an accuracy of 0.5 unit , which is completely permissible.

Foreign investigators have carried out high speed flight simulation, corresponding to M number = 1.2, maintaining an altitude above the earth on the order of 100 m at a mean altitude of obstacles of 300 m, with individual peaks exceeding 600 m, with relief deflection angles of 13%. A block diagram of the simulation unit is presented in Fig. 6.3. /147

The initial view of the display on a cathode ray tube, 125 mm in diameter, is shown in Fig. 7.3a; a view of the display obtained as a result of simulating the system of manual obstacle fly-around, in Fig. 7.3b.

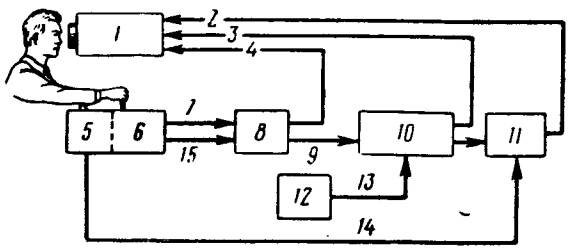

Fig. 6.3. Block diagram of unit for simulating flight with obstacle fly-around: 1. cathode ray tube; 2. maximum value of terrain elevation ahead of aircraft; 3. elevation of three points on the surface of the earth relative to the aircraft flight altitude; 4. horizon and heading; 5. switch; 6. biaxial control device; 7. lateral control; 8. aircraft dynamics; 9. aircraft altitude and bank; 10. spatial position of aircraft relative to surface of the earth; 11. maximum or current value of terrain elevation in 10 sec of flight on aircraft heading; 12. oscillation generator, simulating terrain relief; 13. current value of terrain elevation at three points; 14. reset from maximum value to current one; 15. longitudinal control.

Efforts to execute obstacle fly-around with the type A display turned out to be unsuccessful. The connection between the images of the surface of the earth and the horizon were absent on the display, and the pilot had to interpret two different types of data, superimposed on one another in an incorrelatable manner.[1] Although here, the moving strip of the bank-and-pitch indicator gave a normal orientation of a "from AC to earth" type, its movement was identical to the movement of the horizon visible through the front window. Points T_0, T_5 and T_{10} only partially corresponded with the "from the AC to the earth" principle. When the aircraft gained altitude, these points moved down, which contradicted the principle selected (Fig. 8.3). /148

A change from the angular scale for points T_5 and T_{10} to the altitude scale (75 m/cm), with readings of the altitudes of points T_0, T_5 and T_{10} from the moving strip of the bank-and-pitch indicator permitted execution of a "fly-around" of the obstacle without "collision" with the latter. The pitch angle scale (2.2 degree/cm) was selected from conditions for facilitation of "flying" at an altitude of 75 m above the earth. To facilitate the process of estimation of the altitude of a forthcoming obstacle (points T_{10}), the remembered altitude index of point T_{10} - $T_{10\,max}$ was introduced. As long as the surface (reflecting point T_{10}) remained flat or rose, the $T_{10\,max}$ index coincided with the T_{10} marker. Only when the T_{10} marker began to move downward, designating approach of the peak of the obstacle, the $T_{10\,max}$ index remained in place, indicating the elevation of

[1] This example once again convincingly demonstrates the dependence of the output parameters of the operator-AC system on the type of display and structure of the parameters displayed.

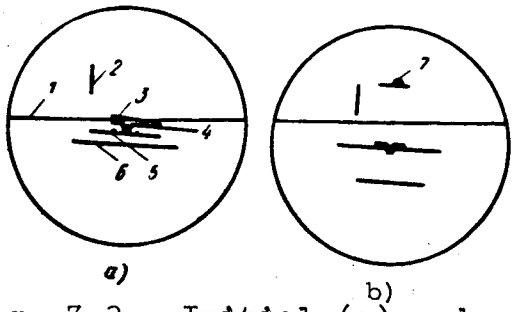

Fig. 7.3. Initial (a) and final (b) view of fly-around indicator: 1. moving bank-and-pitch indicator strip (right bank, diving); 2. heading indicator; 3. marker corresponding to point T_0; 4. stationary bank-and-pitch indicator index; 5. marker corresponding to point T_5; 6. marker corresponding to point T_0; 7. index of stored altitude at point T_{10}.

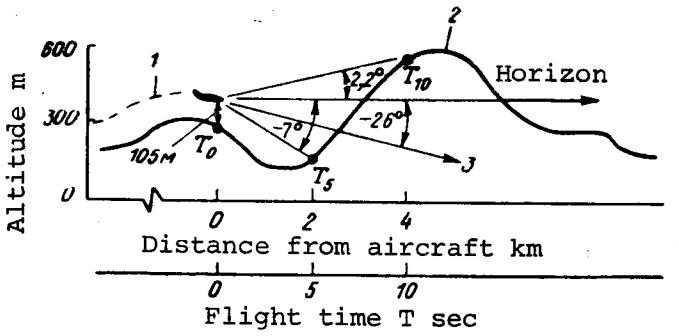

Fig. 8.3. Terrain relief cross section and aircraft flight profile with obstacle fly-around: 1. flight profile; 2. surface of the earth; 3. deflection angle of flight path.

the peak relative to the aircraft. From this moment, the pilot had 10 sec available for moving the $T_{10\ max}$ memory index to the desired altitude below the line of the horizon. Then, by the pilot pressing the button, the $T_{10\ max}$ index again coincided with the T_{10} marker. The maximum magnitude of the "overload" in a manual fly-around of the obstacle, produced with such a display by simulation of a 4 km action distance by the radar, was +3 and -0.5 units. However, analysis of many experiments, according to the data of foreign investigators, has shown that the average pilot can withstand a G-force of +2 and -0.5 unit at the actual frequency of their appearance in flight with obstacle fly-around. Therefore, the value of the initial G-force level was selected as +1 and -0.25 unit . Taking account of these conditions, the radar action distance in modelling manual fly-around of obstacles was 18 km for some foreign aircraft. /149

Many foreign specialists consider that visual orientation, in particular, during flights under clouds and at low altitudes, can turn out to be the only means of detection and identification of small targets, and they should be used for navigation.

The possibility of visual detection of an object located on a uniform background depends on the size of this object and its contrast, and the probability of detection of the object depends essentially on the precision of the piloting. In the opinions of American specialists, if, during flight at low altitudes, the preceding landmark was detected and identified, the probability of detection of a succeeding landmark is very high. If a preceding

landmark was missed, the probability of detection of the following one drops sharply (approximately to 0.5). And so, the importance of mastering the visual landmark method, having a great importance in general and more so during flights at low altitudes, is emphasized.

In conformance with the data of foreign investigators, the distance of detection of an object by an operator from an aircraft is proportional to the square root of the flight altitude, the fourth root of the visibility distance, a negative exponent of the flight speed and the cube of a function, depending on the radius of the object search zone. The latter leads to considerable reduction in the detection distance, even with an increase in uncertainty of its position of only about 100 m overall. With a search zone radius on the order of 200 m, the object detection distance remains approximately constant. With a radius of the zone of uncertainty of its position of more than 200 m, the detection distance again drops considerably. It has been established that division of functions among the crew members (one only observes objects and the other flies the aircraft) leads to a considerable increase in the possibility of search and detection of objects. In the opinion of some investigators [13, 22, 43], a serious shortcoming of the results of laboratory work carried out on detection of objects from an aircraft is the circumstance that, in a number of cases, they are carried out under ideal conditions, in which the dimensions of the object, contrast and meteorological visibility are uniform and the visibility of the objects is evaluated on a uniform background. Under actual conditions, as is well-known, the appearance of the surface of the earth is far from uniform and the search for any sort of object is a very complicated affair, especially if there are a number of masking details and objects of a similar nature. /150

In this connection, the relation between the angular dimensions of the object and its contrast, at which the objects can be detected under real conditions, is given. It is pointed out that, in particular, for detection of an object, the contrast must be approximately 10 times higher than was obtained in the laboratory experiments mentioned. It is important to take these remarks into account in setting up ground modelling experiments.

A problem arises in visual observation of objects and their observation through an optical device, caused by the fact that the operator, in this case, has to adapt to two different illumination levels: inside the aircraft cabin and outside it.

It is easy to see that, for specialists in engineering psychology in aviation and astronautics, in connection with study of the operator-AC system, the landmark has many interesting and still unsolved problems. /151

An operator in an aircraft is placed under time deficit conditions also in the distant and near aerial target guidance stages.

Sometimes in the course of a flight, the pilot may turn out to be under time deficit conditions in bringing the aircraft out of a complicated position, during flight by duplicate instruments, as well as during flight in clouds and at night [38]. Let us examine below the sequence and features of pilot action under these conditions and his interactions with the instruments of the information model.

Under aircraft instrument flying conditions, with the horizon and ground landmarks not visible, the pilot can turn out to be under such circumstances that he does not have a clear idea of the aircraft position in space. In such cases, the pilot must, adjusting to the specific circumstances (mainly to the flight altitude), make a decision as to bringing the aircraft into the normal position or abandon the aircraft.

For these purposes, he must act in this sequence. First, determine the aircraft position in space from the turn and slip indicators, bank-and-pitch indicator and climb indicator, as well as the altimeter and speed indicator. Then, by coordinated movement of the aircraft control surfaces to the side, until there is a reverse deflection of the turn indicator needle, bring the aircraft into straight-line flight, eliminating the aircraft bank and turn. After this, the aircraft is brought into horizontal flight with establishment of the assigned mode.

The distribution and switching of attention to the instruments depends on the nature of the complicated position created (on speed, altitude, bank angle and deflection angle of the flight path). However, in all cases, the main attention should be given to the turn and slip indicators and climb indicator, monitoring the aircraft position by the bank-and-pitch indicator.

Under instrument flight conditions, failure of one instrument or group of instruments or another is possible, for a number of reasons. For example, after executing certain acrobatic maneuvers, the bank-and-pitch indicator may be "knocked out" or completely fail to operate. Upon freezing or clogging up of the pitot-static line, the speed indicator and M meter refuse to work.

With defects in the static line, the altimeter and climb indicator (as well as the speed indicator and M meter) fail. In a number of cases, the gyromagnetic compass (power cutoff, coordination system breakdown and other things) and the automatic radio compass (aircraft electric power supply and other things) may fail. /152

First of all, the pilot must be trained in timely and rapid determination of failure of one instrument or group of instruments or another. After detecting the failure, the task of the pilot is having the skill to switch over to flying by other flight-navigation instruments, duplicating the readings of the failed instruments, keeping in mind that there is a unique interchangeability of the readings of separate instruments or groups of them in an aircraft [12].

Failures of the bank-and-pitch indicator or erroneous readings on it (as to lateral bank) can be detected easily by comparison of the bank-and-pitch indicator readings with the readings of the turn and slip indicators. Thus, if a pilot maintains a zero bank of the aircraft (according to the bank-and-pitch indicator) in horizontal flight, with an inaccurately operating or failed bank-and-pitch indicator, the aircraft, naturally, will be banked and begin to depart from the assigned heading, which will be noted on the turn indicator and compass, and the bank-and-pitch indicator defect is detected immediately. Inaccurate bank-and-pitch indicator readings during turns of the aircraft result in the turn indicator readings and the rate of change in heading according to the compass not corresponding to the value of the bank.

Incorrect pitch readings on the bank-and-pitch indicator result in the readings of the climb indicator, speed indicator and altimeter not corresponding with the readings of the bank-and-pitch indicator on the longitudinal bank scale, and the incorrectness of the bank-and-pitch indicator or its failure to operate will be noticed.

In case of failure of the bank-and-pitch indicator, the aircraft can be flown by the turn and slip indicators, compass, climb indicator, speed indicator and altimeter.

Horizontal flight, climb and descent modes can be maintained by these instruments without the bank-and-pitch indicator. In particular, the transverse equilibrium of the aircraft can be maintained by the turn indicator needle (zero reading) and slip indicator (ball in the center of the scale). In this case, the aircraft will not have a lateral bank. /153

Retention of the longitudinal equilibrium of the aircraft can be provided by use of the climb indicator and altimeter, the readings of which, at a constantly increasing speed (monitoring on the speed indicator), should correspond to the assigned mode of change in vertical speed and altitude.

To retain longitudinal equilibrium in any flight mode, movement of the control surfaces should be brief and "double." Efforts of the pilot to restore the assigned speed by one application

leads to sharp movements of the control surfaces, which causes considerable deviations in speed from the assigned speed and longitudinal oscillations of the aircraft.

Retention of heading equilibrium is controlled by the compass (the assigned heading is maintained).

Failure of the speed indicator and M-meter is determined, as a rule, by the behavior of their needles: the sensitivity of the instruments to change in the flight modes is greatly reduced; frequently, the readings of these instruments can drop to zero upon failure. This means that, for determination of failure of these instruments, an effort must be made to change the flight mode and monitor it by the bank-and-pitch indicator, climb indicator and altimeter.

Flying an aircraft upon failure of the speed indicator in horizontal flight, while climbing, descending and turning, can be carried out by the pitch angle indicator in the bank-and-pitch indicator and engine rpm corresponding to the given flight mode. In this case, a given mode is monitored by the climb indicator, altimeter, compass and turn indicator.

It is most complicated to execute a descent at low altitudes during failure of the speed indicator. The complexity is that, in proportion to decrease in flight altitude, the vertical rate must be gradually decreased and, consequently, the pitch angle must be changed. In accordance with these changes, to maintain a constant forward speed during a descent, the engine rpm must be increased, which requires precise distribution of attention to the readings of the instruments and complicates the work of the pilot. The pilot also should know the exact values of the pitch angles and the engine rpm corresponding to them in all modes. /154

Failure of the altimeter and climb indicator to operate, due to trouble in the pitot-static line (during which the speed indicator and M-meter get out of order) usually also is determined by the behavior of the needles of these instruments. In horizontal flight, the readings of the speed indicator, altimeter and variometer do not change. In climbing, the readings of the speed indicator are decreased (and go to zero during a long climb), the altimeter readings do not change and the climb indicator needle drops sharply to zero. In descending, the speed indicator needle smoothly moves in the direction of an increase in the reading, and the altimeter and climb indicator needles behave just as in climbing.

The aircraft is flown by the bank-and-pitch indicator, using the tachometer. In this case, much attention must be given to monitoring the flight altitude, which is accomplished by the altitude indicator in the pressurized cabin, as well as from earth by radar measurements.

Failure of the compass and automatic radio compass is determined by constant comparison of their readings during an actual change in aircraft heading.

During failure of one of these instruments, it can be duplicated by other instruments, as well as by ground direction finders and radars.

V. A. Ponomarenko, A. L. Avayev and N. D. Zavalova [66] conducted research on optimization of principles of coding signals of failures of automatic control in a time deficit.

In the opinions of the investigators, the effectiveness of signal indication of failures of automatic machines in control systems, where rapid and precise motor reactions to the failure are required of the operator, are determined, not only by the strength of the signal stimulus, but by the command value of the signal. The command should tell the operator of the developing emergency situation.

Flights in clouds with modern aircraft equipment and sufficient ground provision for aerial navigation, present no difficulty. The flight crew, skilled in instrument flying, quite easily executes flight missions in both clear weather and in the presence /155 of cloud cover and various atmospheric phenomena -- rain, snow, fog.

How is flight in clouds characterized?

First, flight in clouds is characterized by the absence of visibility of the earth and the natural horizon; second, an aircraft in flight is subject to the action of many atmospheric phenomena, connected with being in a cloud layer.

Experience shows that flights in clouds are distinguished from flights under simple meteorological conditions, and even from instrument flights in a closed cockpit, by a series of features, of which the pilot must have a clear conception.

An experienced pilot, entering the clouds, behaves quite calmly towards the situation created and confidently continues to fly the aircraft along the assigned route. A pilot getting into the clouds for the first time begins to worry and loses confidence in his capacities for flying the aircraft by instruments. If the cockpit of a pilot learning to fly by instruments, but not flying in clouds, is closed by a "hood" and, unnoticed by him, the aircraft flies into clouds, he will be just as confident of flying the aircraft as outside the clouds; he needs only to open the cockpit and see that he is in clouds, and the quality of his flying can deteriorate.

Everything is explained here by the fact that, during instrument flight (in the absence of clouds), the pilot gives all his attention to the instruments, but in flying in clouds, attention is distracted to the visible parts of the aircraft, to the changing density and color of the clouds, to rain, snow, and icing. In this manner, the sequence developed for distribution and switching attention is disturbed and piloting quality is reduced.

Flight in clouds is accompanied by bumpiness, especially in penetrating underneath clouds and in flight under clouds with a low cloud bottom height. In this case, maintenance of the flight mode becomes difficult and the necessity for accuracy in maintaining it increases.

It is considerably more difficult in night flights than in day ones to accurately determine the distance to the earth and the altitude to start leveling off and holding, which leads to certain difficulties in execution of a landing by the pilot.

Night flight conditions, during flight in an illuminated cabin, have a negative influence on adaptability of the visual organs to observation of objects from the aircraft. The night flight situation, in comparison with the daytime one, causes a certain stress on the psychic condition of the pilot, which can show up, in a number of cases, in the quality of flying the aircraft by instruments. /156

Time deficit conditions in a flight can be aggravated by the emergence of illusions of the spatial position of the aircraft in the pilot. Illusions are distorted perceptions of phenomena, when the actually existing phenomena are perceived in disparity from their actual content. Illusions of spatial position are incorrect, false sensations (vestibular, muscular, cutaneous and the like) of the position of the body (as well as of the flight craft) in space. Illusions complicate the execution of actions, make the piloting technique worse and, in individual cases, lead to loss of spatial orientation.

The presence of illusions can be established by comparison of the personal feelings of the pilot (astronaut) with the visual perceptions of the instruments of the information model of flight, which correctly indicate the AC position in space.

The illusion of banking arises frequently (during horizontal flight), gliding and pitching (during change in flight speed) and varieties of them: a feeling of climbing while turning, descending while coming out of a turn, banking in the opposite direction when slipping, turning in the opposite direction after coming out of a bank and illusions of inverted flight.

In distinction from the illusions mentioned, there also are visual illusions of light reference points (the stars taken as a navigation light, reflection of the sun or star in a cloud as the real star, ground beacons as stars), visual illusions from clouds (during flight over clouds or between cloud layers, which are not located horizontally, these clouds are taken as the natural horizon and the aircraft is "flattened out" according to this "horizon"); illusions of immobility of the aircraft or formation of aircraft (at high altitudes in the stratosphere or during flight in formation and with poor visibility of the horizon, sometimes at high angles of climb, when the horizon is not visible).

Ye. A. Derevyanko and V. G. Kuznetsov present the following relative data on the frequency of manifestation of individual types of illusions (in percent): /157

illusions of banking, 45;
illusions of pitching, gliding, 22;
optical illusions, 11;
illusions of inverted flight, 9;
illusions of immobility of the aircraft or formation of aircraft, 5;
other illusions, 8.

As a rule, illusions most often are manifested in a pilot at the beginning of his instrument flight training, but not on every flight. In many individuals, they can appear in all such training flights.

Illusions can continue for from several seconds to several minutes. Prolonged illusions cause considerable emotional stresses and fetter aircraft control movements (movements become abrupt and uncoordinated).

The causes of illusions lie in the physiological features of the interactions of human sense organs in flight. For example, during the action of G-forces , the vestibular apparatus, participating along with vision in formation of a three-dimensional representation, loses the capacity for correctly signalling the true position of the body in space; by distraction of the attention of the pilot from the instruments, distorted information from the vestibular, musculoarticular and other sense organs can have a harmful, undesired effect on the central nervous system of the pilot and lead to illusions. Weak instrument flying skills, interruptions in flight training, change from one type of aircraft to another, individual peculiarities and other things should be included in the factors facilitating the emergence of illusions. Methods of control of the onset of illusions follow from the reasons discussed. They include mainly purposeful training of the pilot in maintenance of the flight mode.

Probably, the use of displays on the lateral window also will facilitate the elimination of certain causes of illusions (it eliminates or reduces to a minimum quantization and intermittency of perception of the artificial horizon readings).

The takeoff stage of an aircraft, beginning with the run and /158
ending with gaining an altitude of 50 m after breaking away from the earth, stands together with such rapidly moving and difficult flight stages as landing and homing on a target in complexity of its execution.

In the takeoff process, the pilot must correctly determine and maintain acceleration of the aircraft, pick up the necessary takeoff speed, maintain heading and position of the aircraft relative to the longitudinal axis of the runway, determine and set the aircraft takeoff mode from the runway and climb mode.

In this case, the pilot must take account of the length of the aircraft run, runway length, nature of the runway surface, weight of the aircraft, wind speed and direction, air pressure and temperature and a number of other moments determining the takeoff properties of the aircraft.

A simple listing of the factors affecting the quality of an aircraft takeoff, consideration of which, of course, is necessary for the pilot in executing a takeoff, also tells of the difficulty of executing this stage of flight. If the possiblity of complicated meteorological conditions during takeoff is added to this, the necessity for systematic training of a pilot for executing takeoffs and the use of special instrument equipment in this phase of flight become completely obvious.

Let us examine several possible instrument systems for controlling the takeoff of an aircraft [22].

Among the onboard equipment, one of the systems uses an accelerometer for measurement of the aircraft acceleration in takeoff, in combination of measurement of the dynamic pressure. Both alarm signals and visual indications of acceleration are given in the system, by a special instrument in the cockpit.

The pilot only has to set on the instrument the takeoff weight of the aircraft and the planned acceleration, the value of which he determines with a slide rule or nomogram, on the basis of data on aircraft shape, surrounding temperature, pressure, runway slope and engine mode. This system does not require any manipulations by the pilot at the beginning of the run. However, in some aircraft, compensation for small changes in the pitch angle, caused by a different location of the center of gravity, may be required. As a result of this, the acceleration sensor is somewhat

displaced from the initial horizontal position and reacts to the acceleration of gravity. Calculations show that a change in pitch angle of 1% in heavy jet aircraft can lead to an error of almost 10% in measurement of the linear acceleration. Such an error is equivalent to the difference between normal and inaccessible takeoff mode conditions. In view of this, the necessity for pitch correction signals from the aircraft vertical gyro can arise. /159

During the run, the indicator needle shows the pilot whether the aircraft acceleration is normal, high, or low. The cross-hatched section of the scale corresponds to a dangerously low acceleration. Acceleration of a jet aircraft at constant thrust is somewhat decreased in proportion to increase in run speed, as a consequence of an increase in d r a g. To compensate for this normal reduction in acceleration, the accelerometer signal is added to the signal from the dynamic pressure sensor. The sum of these signals remains constant during all of a correct run and does not depend on the wind at the airport, which allows not putting the wind data into the system.

Onboard takeoff mode control equipment of another system provides continuous measurement of the distance covered by the aircraft on the runway and determination of its runway speed. At a given distance, a comparison is made of the actual runway speed and its planned value, which the aircraft should have reached at this point. Planned values of the runway speed (determined by slide rule) and the check distance are set by the pilot on a panel (comparator) located in the cabin. This is a display, with numerical indication of the distance covered and a signal lamp.

A small pulse generator, installed on the main landing gear wheel, is used for the distance measurement. When the aircraft reaches the assigned checkpoint on the runway, a comparison of the speed signal with an electrical voltage, corresponding to the assigned value of the speed, is carried out in the comparator. A blinking green light of the signal lamp indicates an acceptable run speed and a blinking red light, too low a speed.

This system permits the pilot to check the individual parts of the system before takeoff, using one of two methods: /160

1. By pressing the "Taxi" button on the display before taxiing to the start position, the runway measurement system begins to operate, which makes it possible to check the operation of the distance sensor and certain other circuits while taxiing;

2. By pressing the "Check" button on the comparator, a signal is produced, which is equivalent to one full revolution of the main wheel. The pilot can press the button a given number of

times and check whether the resulting distance reading of the counter corresponds to the distance covered.

Before beginning the run, the pilot must press the "Takeoff" button on the display. The latter operation can be automated.

Finally, a third system measures the runway speed, calculates the acceleration and compares them with the assigned standard values.

An indicator in the cockpit gives the pilot continous information on the relative value of the actual acceleration of the aircraft during the run. The system does not require preliminary calculations by graphs or slide rule. It is only necessary to set the runway length and wind speed on the display. Compensations for change in the barometric pressure are made automatically, with the aid of an aneroid unit connected to the aircraft pitot tube. In the simplest version, the system is calibrated at the maximum takeoff weight of the aircraft. In a more precise version, the takeoff weight must be put into the system as an initial parameter. Compensation for reduction in acceleration with increase in speed is provided. The indicator works on the "yes-no" principle, without a numerical scale.

In England, in instruction on the technique of flying for each aircraft, a minimum speed is provided for, which must be attained at a specific point on the runway, in order for the aircraft, taking off at this point can gain an altitude of 15 m or, in case of a forced termination of the run, remain within the runway (using emergency braking). Since continuation or termination of the run is connected with the pilot making a specific decision, the minimum speed guaranteeing a safe run is called the /161 "decision-making speed" in the instructions. Experience has shown that the regular speed indicator does not allow the pilot to execute full control over the progress of the run, and it requires a special instrument which would measure the increase in speed over the entire length of the run.

Before takeoff, the pilot sets a given minimum speed value on the instrument counter, with account taken of the specific takeoff conditions. The instrument scale is divided into two sectors, green and red. If the instrument needle, connected with the airspeed sensor, remains on the border between the sectors during the run, this means that the takeoff is proceeding normally, i.e., the actual speed is equal to the planned speed. The position of the needle in the green sector "tells" that there is reserve speed and, within the red, indicates insufficient speed. A graduation corresponding to the runway length can be applied to the instrument scale. It is thought that use of such an instrument considerably increases flight safety.

Concerning determination of the aircraft heading during takeoff, for this purpose, a standard onboard instrument, the compass, is used successfully.

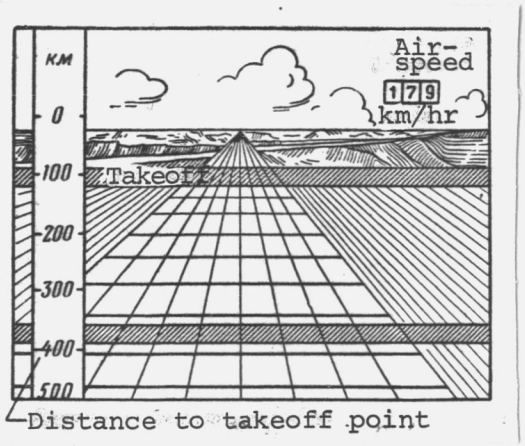

Fig. 9.3. Appearance of electronic-optical visual flight analog indicator in takeoff mode.

At the present time, direct measurement of the deviation of the aircraft from the central runway axis by simple means has not succeeded. However, it can be asserted that, if the aircraft at the head of the runway is precisely set along the runway axis and the assigned takeoff heading is maintained precisely during the run, at the moment of takeoff (with accurate compass operation) it proves to be practically on the central runway axis and, in this respect, control of one of the takeoff parameters can be considered guaranteed.

A visual flight analog type of apparatus can be used for indicating the takeoff process. The appearance of the face of one of the electronic-optical visual flight indicators (in the takeoff mode) is shown in Fig. 9.3.

Operator-AC systems being discussed and working conditions of the operator during their operation, are greatly different from the accustomed ground systems, and have been quite extensively studied by specialists in general engineering psychology. /162

For development and substantiation of requirements for creation of such aircraft systems and substantiation of methods of training operators for professional activities, special laboratory and flight research has to be set up, which has great difficulties connected with it.

CHAPTER IV. MAN-MACHINE SYSTEM UNDER G-FORCE CONDITIONS AND DURING VIBRATIONS /163

The G-forces accompanying AC flight and acting on the human body are a consequence of accelerations arising during any change in AC flight speed in magnitude or direction. G-forces unfavorably affect the human body, the information and energetic functions of the operator, and, as a rule, reduce his efficiency.

In aviation and space medicine, the accelerations of interest to engineering psychologists are divided into several groups:

a) Linear acceleration, arising during change in magnitude of speed (but not in direction), in straight-line aircraft flight: takeoff, landing, increase or decrease in forward flight speed en route, during flight of a spaceship at the start of the active portion and during descent in the atmosphere, during orbital flight of a spaceship, when switching on and switching off engines for executing maneuvers, etc.;

b) Centripetal acceleration, arising during a change in direction of movement, in executing various aircraft maneuvers of the turning and acrobatic types, during change of a spacecraft in the active section of the flight from the vertical direction to the orbital entry flight path and others;

c) Angular acceleration (tangential and perpendicular), arising during change in the angular velocity of AC movement;

d) Coriolis acceleration, arising during simultaneous combinations of rotation and straight-line movement.

When executing acrobatics in aircraft, the G-forces [1] can reach values on the order of 6-8 g, and their duration of action can fluctuate from several seconds to several minutes. /164

The magnitude and duration of the action of G-forces during takeoff and landing of a spacecraft depend on the program for jettisoning the carrier rocket and the aerodynamic characteristics of the ship. The magnitudes and duration of the accelerations to which spaceship crews can be subjected considerably exceed the maximum magnitudes of acceleration of the most powerful jet aircraft. In launching an aircraft from a catapult, forces of 3-4 g act on the pilot in the lateral direction for a period of 3 sec.

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[1] G-forces acting on a man, as well as on AC structural elements, are measured by the ratio of the actual acceleration to the normal acceleration of gravity. Thus, a G-force is a consequence of acceleration, arising during nonuniform movement of the AC.

The nature of the action of G-forces on the operational capabilities of man depends on the magnitude of acceleration, the period of its action, recurrence (frequency) of the action, direction with respect to one axis or another of the body, sharpness (gradient) of increase and decrease, fluctuation in magnitudes (smoothness of the change curve), sensitivity of different operator systems to it under conditions of a moving and changeable situation and individual characteristics of the body.

During action of G-forces from the head to the pelvis (longitudinal direction), pressure on the seat increases, heaviness in the head and temples is manifested, the diaphragm sinks, the lower part of the body swells and visual functioning deteriorates.

During the action of G-forces in the chest-back direction (lateral direction), heaviness and pains are felt in the chest.

The magnitude of G-forces which man can withstand and the time of its action usually is (within specified limits) an inverse function: the shorter its time of action, the greater the G-force the operator can withstand. One and the same G-force over uniform segments of time of its action in the lateral direction is more easily withstood by man than during /165
action in the longitudinal direction. This is why no one single value of the maximum sustainable G-force can be indicated. There are many criteria by which the limit of sustainable G-forces is determined (for example, disturbance of vision, disturbance of respiration, inadequate functioning of the muscles, etc.).

During numerous investigations, it has been determined that the optimum posture for spaceship crews, from the point of view of bearability of acceleration, is the semireclining position in an armchair, when the G-forces act in the transverse direction to the axis of the body [9].

It is known that the efficiency of a man, as operator, during the action of G-forces, is determined to a considerable extent by the functional condition of the sense organs, especially vision, and central nervous system (its higher sections), as well as the degree of mobility of the working organs.

During the action of G-forces in the head-pelvis direction, different manifestations of visual disturbance are observed most often and, depending on the magnitude, duration and other G-force characteristics, it "clouds up" and peripheral vision is weakened (the field of vision is decreased), peripheral vision completely disappears and central vision is weakened, and, finally, total loss of vision sets in ("blackout").

Possible disturbances of physiological functions in the operator during the action of G-forces are presented in Table 9.

TABLE 9. (FROM U. WOODSON AND D. CONVER) THE EFFECT OF PROLONGED G-FORCES

Reaction of man to different G-forces	Acceleration
2 g - Reduction in visual acuity 4 g - Difficulty in extensive body movements 8 g - Difficulty in breathing 10 g - Difficult to hold the head possible to move the extrem 12 g - Difficult to breathe without mechanical aid 14 g - Vision begins to fail	Transverse (back-front)
2 g - Reduction in visual acuity 4 g - Peripheral blindness, move extremities difficult 5 g - Temporary blindness and l ɔn-trol of body 6 g - Loss of consciousness	Positive
2 g - Deterioration of vision, headache 3 g - Hemorrhage in the mucous membranes of the eyes, reddening of the face, dulling of mental activity 4 g - High probability of internal hemorrhage and loss of vision	Negative

As a result of visual disturbance, the conditions for observation of the instruments and other devices of the information model deteriorate, as a consequence of which a slowing in the beginning of motor reactions to stimuli (light and sound) is noted.

During the action of G-forces exceeding the individual tolerance threshold, reduction in the quality of solutions of psychological problems, distinct slowing of reaction time (right up to complete disappearance of conditioned reflex) and disturbance of precise motor coordination are noted. The maximum muscular effort of the operator's arm also decreases during G-forces , and their smoothness and uniformity are disrupted. During forces

of 3-4 g (head-pelvis), control over voluntary movements is lost, and the man is in a condition to make only small movements of the arms. The average time for manipulation of different controls changes sharply under G-force conditions (Fig. 1.4). /166

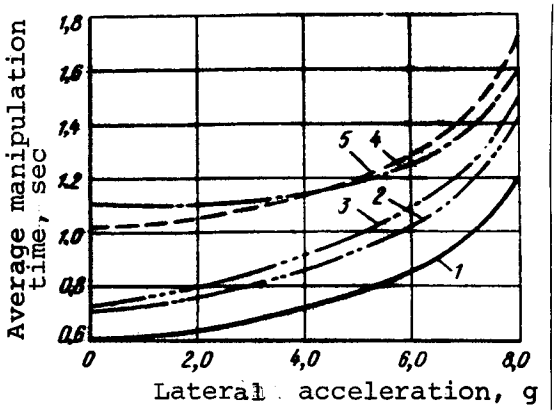

Fig. 1.4. Operator controls manipulation time vs. G-forces; 1. lever; 2. control column; 3. control stick; 4. switch; 5. switch button.

It has been determined (Fig. 2.4) that, during G-forces of more than 6 g, mobility of the large joints of the arm and leg is impossible. The wrist and fingers retain adequate mobility during G-forces of 8 g. During G-forces of 15 g, the subject can execute certain movements of the wrist and fingers, but mobility of the joints is reduced to a considerable extent. A conclusion is drawn from this: if G-forces of more than 4 g act on an astronaut, control of the ship under acceleration conditions must only be automatic. However, this conclusion is not confirmed by a number of other investigators, since the "operator resistance" to G-forces can be increased by both purposeful training and by improvement in the internal construction of the manual control system of the AC during launch and use of more effective technical means in the information model. /167

Fig. 2.4. Limiting G-force values (with respect to joint mobility).

Accelerations arising during aircraft "bumping," rolling, "yawing," as well as in flying around obstacles during flights at minimum altitudes, have a strong effect on operator efficiency. Foreign researchers have carried out experiments to clarify the effect of oscillatory motions of an aircraft in flight, accompanied by G-forces , on the crew.

The research was carried out in a two-seater airplane by three pilots and three navigators [82]. Oscillatory motions were created by means of the control stick. In the banking plane, oscillations of 0.25-2.5 Hz were used and, in the pitch plane, 0.25-1.0 Hz. The maximum angular velocity in the first case was 2-10 and, in the second, 3-6 degree/sec. Twelve different conditions were studied in the banking plane and only six in the pitch plane, as a consequence of the rapid onset of nausea. Each /168

maneuver was continued for 30 sec. The subjects estimated the effect of these maneuvers on control of the ship, vision and subjective feelings of the pilot. Among the objective tests were multiplication and division on a slide rule and rapid reading aloud of a standard text. Lateral G-forces of less than 1 g did not show a significant effect on the state of health of the pilot; G-forces of 1.0-1.5 g caused some agitation and, of 1.5-2.0 g, serious disruptions of efficiency. The authors consider lateral G-forces of a magnitude of more than 2.0 g unbearable. Oscillatory motions in the pitch plane caused vomiting of all subjects. Vomiting set in more rapidly at a ship oscillation frequency of 0.25-1.0 Hz. Oscillatory motions in the pitch plane caused the illusion of deformation of a test item, a circle with 72 radii. The illusions increased with increase in frequency and amplitude of the oscillatory motions of the ship. Problem solving and reading were not disturbed. The authors consider the maximum value of the G-force during oscillatory motions to be the most significant criterion in evaluating the bearability of oscillatory motions of aircraft. At a linear G-force value of oscillatory motions of less than 0.1 g, the conditions examined were completely bearable in the region of the head and, at 0.2 g, they became absolutely unbearable.

At the present time, it is considered established that, with increasing G-forces, one and the same amount of working activity is carried out by a man with considerable stress on the neuromuscular activity and, qualitatively, with poorer characteristics than in the initial state. However, it is known from aviation practice that, in the process of repetition of flight missions and acrobatics of continually increasing complexity, the activity of the pilot in control of the aircraft is gradually facilitated. /169

Comparatively much research has been carried out on the actions of G-forces on the human body, both at home and abroad; however, for the most part (in the schedule of engineering-psychological research) they have been limited: the operators were given simple problems in control, requiring an elementary response or transmission of an arbitrary signal. In this case, of course, it was impossible to evaluate the dynamic properties of the operator and his psychophysiological capabilities in control of the various objects sufficiently carefully [25].

Control of a spaceship after its descent from orbit for landing is an extremely complicated scientific-technical problem. The basic peculiarity of this stage of flight of the ship is the fact that descent of the ship, for example, during flight in the atmosphere of earth, is possible only in a comparatively narrow corridor, the boundaries of which are determined by the permissible heating of the ship skin and the permissible values of braking G-forces for the structures of the ship and of its crew [94].

Moreover, the descent must guarantee landing of the ship in a given region. All this leads to the necessity for controlling the ship so that its descent takes place, not on an arbitrary flight path, but on the optimum one for the given conditions. Complex conditions for the control work of the operator, in the presence of long-acting G-forces , forces the ship designers to carry out calculations on a completely automatic control system, autonomous in its action, and to restrict the maximum G-force. The first requirement also provides return of the ship when the crew is incapable of control. However, together with this, to increase the reliability of the system, the capability of manual control is provided for, just the same.

In discussion of the features of the ship descent control system, it should not be forgotten that the descending craft, as an object of control, does not have adequate stability or damping, and it also has relatively low aerodynamic qualities. /170

As follows from what has been said, the ship descent control system also will have its characteristics, from the point of view of the psychophysiological capabilities of the operator, especially if account is taken that G-forces will act on the operator after his prolonged stay under weightless conditions. All this requires efficient organization of the manual control circuit and proper preliminary training of the astronaut.

The general functions placed on the operator during landing of the AC after descent from orbit are: monitoring the automatic descent control system, introducing (as necessary) corrections into the operation of the automatic system and manual control of the AC during descent.

In the latter case, the operator, under conditions of the actions of G-forces, must control the movement of the AC by instruments relative to the calculated flight path while plunging into the atmosphere and during descent, as well as (in the case of a second entry into the atmosphere) orienting the longitudinal axis of the AC relative to the assigned direction before this entry.

The characteristics of the operator in the control circuit were investigated with and without G-forces and with an unchanged command signal structure and constant controllability and stability characteristics of the object. The nature of change in the command signals, actions of the operator on the controls, change in the parameters of longitudinal movement of the object and data on the psychophysiological condition of the operator were recorded by means of a complex system of monitoring-recording equipment.

Operators who had completed the cycle of preliminary training in control of an object and who had experience in sustaining G-forces were drawn into participation in the experiment. Processing and analysis of the flight parameter and operator characteristic recordings permit certain generalized conceptions to be compiled on the psychophysiological capabilities of man in control of an aircraft under G-force conditions.

In the absence of G-forces, all operators successfully coped with control of the object. The root mean error in holding the needle of the command instrument was no more than 0.6° under these conditions. In the process of control, no sharp deflections of the control surfaces were generated, and oscillations of the controllable flight parameters were successfully eliminated by the operator. The time of working out a signal, presented in the form of a deflection of the command needle, amounted to no less than 20 and no more than 35 sec. /171

Control under G-forces of up to 4 g was not accompanied by noticeable decrease in the transition processes in the angular and flight path movement circuits. The mean duration of the processes increased somewhat and amounted to 25-40 sec.

Upon increase of the G-force to 6 g, the quality of control begins to deteriorate somewhat. The amplitudes of oscillations in the controllable parameters increase by a factor of 1.5-2. The operator brings the aircraft to a flight mode which is significantly different from the initial one, only with difficulty.

With further increase in the G-forces , a limit is reached, beyond which the operator generally cannot cope with control, and permits sharp deflections of the control surfaces, as a consequence of which diverging oscillations of the controllable parameters and large changes in the G-forces along the longitudinal axis of the aircraft arise. The control circuit, including the operator, becomes unstable.

It must be noted that, after termination of the G-force action, the operator quickly regains his efficiency and flies the aircraft just as he did before the action of the G-forces.

Study of the neuropsychic activity of the operator was carried out simultaneously with study of the control process dynamics. The polyeffector method of recording physiological functions was used in the investigations.

Experimental data obtained by recording the physiological functions show that the magnitude of the bioelectric activity of the low frequency cerebral cortex rhythms increases somewhat, with

respect to the background data of rest and control, after the action of lateral G-forces of 4,6 and 8 g. Thus, for example, after the action of a 4 g force, the readings of the bioelectric activity of low-frequency rhythms increased by 28% on the average, and after the action of an 8 g force, by 33%, with respect to the background data. At the same time, with increase in longitudinal G-forces, a reduction in the quantitative and qualitative indications of working activities took place. /172

The changes in the bioelectric activity of the low-frequency cerebral cortex rhythms mentioned, apparently are evidence of a reduction in lability of the nerve cells and of the development of protective inhibition processes in the cerebral cortex. For this reason, the inertia of the operator as a dynamic link in the control system (time constant T_0) increases.

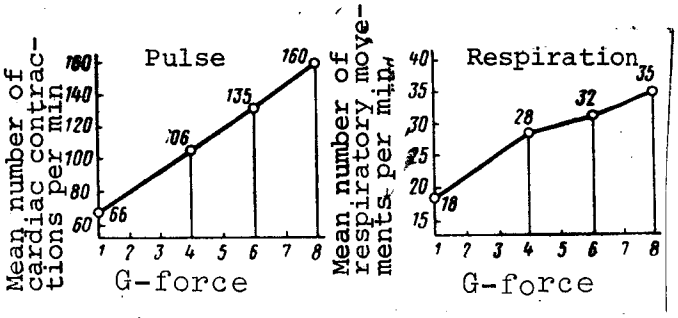

Fig. 3.4. Change in pulse and respiration of operator vs. G-forces.

In execution of control operations under conditions of increasing G-forces, significant changes were observed in the vegetative reactions of the body (pulse, respiration). During the period of control in a 4 g force, the number of cardiac contractions increased by 75% on the average and the number of respiratory movements by 68% and, with an 8 g force, the number of movements increased by 75% over the background data (Fig. 3.4). The changes mentioned are regular compensatory acts under conditions of the unfavorable action of increasing G-forces on the body.

During the action of G-forces on the operator, significant increases in the readings of bioelectric activity of the muscles were observed. The mean value of the bioelectric activity of the muscles of operators vs. G-force is shown in Fig. 4.4. The relationship presented is expressed in percent of background data, obtained during the control process in the absence of G-forces, and they show that the magnitude of the bioelectric activity of the muscles increases in proportion to increase in G-force. Thus, in executing control operations under conditions of a 4 g force, the magnitude of the bioelectric activity increased by 103%, by 113% at 6 g and by 230% at 8 g. /173

Changes in bioelectric activity of the muscles of an operator vs. G-force ($EMG_{\mu V} = f(n)$) are shown in Fig. 5.4.

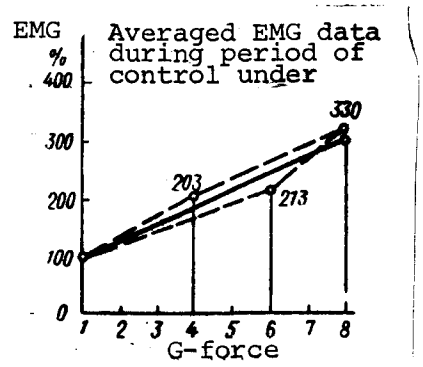

Fig. 4.4. Mean value of bioelectric activity of muscles vs. G-force (EMG = f(n)).

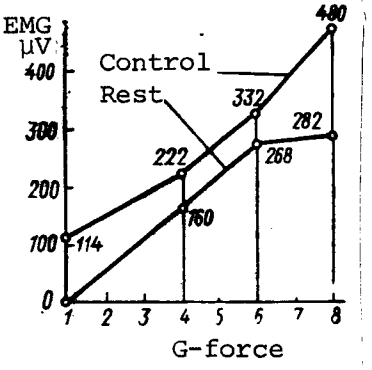

Fig. 5.4. Change in bioelectric activity of muscles of operator during G-forces ($EMG_{\mu V}$ = f(n)).

The results of experiments have shown that, under conditions of the action of G-forces not exceeding a specified level, the operator is able to control angular and flight path movements, if he receives a single control command. The structure of the control command must be identical to the control pattern of the automatic system. Besides, corrections must be made in the command system, adjustment of the dynamic characteristics of the operator. The choice of the optimum structure of the command control can be made by the methods used for automatic control system [9].

Manual control system methods during descent of an AC can differ from those discussed above. Control of certain parameters during AC descent can be laid on a completely automatic system (for example, bank stabilization and others). Stabilization of the AC axis relative to the velocity vector can be provided by damping systems and others. A system in which the operator acts on the controls, depending on the mismatch in G-force (difference between instantaneous and planned G-forces) or using G-force mismatch instruments and the derivative of this mismatch, can be used. Display devices in the information model can be diverse, but adapted for rapid and precise perception by the operator of data furnished to him. /174

The usual visual needle displays, because of the effects of G-forces on functioning of the visual analyzer of the operator, cannot always meet the complicated conditions of G-forces in flight. The development of more highly visible and easily read displays may be required (for example, with a wide white window, part of which is "filled" with a black color, depending on the value and sign of the mismatch of the actual and planned flight path parameters). Visual displays can be duplicated or supplemented by acoustical-sound devices and, in particular, by devices for measurement of the mismatch between the planned and current flight path parameters. Sound pulse mismatch indicators (for the right and left ears), supplying sound pulses 0.15-0.2 sec long, with a repetition frequency of 4-6 Hz and tone pitch of 500-3500 Hz (depending on the magnitude of the mismatch in the parameter measured), have demonstrated quite good results.

The controls also should "approach" the working conditions of the operator during the action of considerable G-forces. In particular, in place of the widely used control sticks or columns, buttons (or keys) can be used.

Thus, in craft descent control systems, by virtue of the specific working conditions of the operator and the special requirements for the craft descent flight path, as well as the peculiarities of its dynamic characteristics, it is extremely important to take into account the psychophysiological capabilities of the operator and to match them with the characteristics of the technical components of the control system.

Naturally, different AC descent control systems apply specific impressions to the operator control activity, which must still be tested before AC flights in modelling test units coupled with a centrifuge. /175

In the research of professor S. A. Gozulov and N. I. Frolov [17], disturbance of the efficiency of the operator after the action of impact G-forces of various magnitudes was noted. The authors determined that muscular efficiency after the action of repeated impact G-forces of increasing magnitudes seemed to go through three stages: a stage of primary reinforcement of efficiency; a stage of discoordination; and a stage of reduction in efficiency.

In analyzing the problem of control of the adverse effects of acceleration, caused by G-forces, the circumstance should be taken into account that it is practically impossible to eliminate it in flight and control of its effects is possible only by way of increasing the resistance of the body and by creation of conditions which permit all harmful effects to be borne more easily.

The most convenient protection for the pilot from the effects of acceleration is the G-suit . It must be kept in mind that the effectiveness of the protective action of the suit depends on its adjustment and the mode of operation of the automatic pressure machine [40].

The G-suit increases the resistance of the body to the action of G-forces by 1.5-2.0 g on the average. Its use decreases pilot fatigue, arising after the actions of G-forces. Under space flight conditions, the space suit increases the safety of astronauts in portions of the flight with G-forces : in bringing the craft into orbit and during the return to earth.

Research was carried out under laboratory conditions to determine the effect of respiration under increased pressure on the capacity of man to carry out complicated psychomotor tasks during

periods of high, prolonged acceleration and to distinguish the brightness of light signals during lateral and positive accelerations. The results have shown that breathing 100% oxygen under increased pressure improves perception and accomplishment of psychomotor tasks during prolonged, high, continuous acceleration. According to a number of signs (comfort, endurance, ease of breathing), lateral accelerations were endured more easily while breathing under increased pressure. /176

Pursuit of such types of sports as two-man gymnastics, acrobatics, volley ball, heavy athletics and mountain climbing increase resistance of the body to the action of prolonged G-forces.

Among the special types of training are rotation in centrifuges, calisthenics, Rhine wheel, vertical swing, swings, merry-go-rounds and flights in aircraft under the action of G-forces.

Vibrations (from the Latin vibratio, oscillation, shaking, tremor) are mechanical oscillations of material points or bodies. Usually, vibrations taking place with a frequency of approximately 1 oscillation per second and more are called oscillations. Data on typical bearability of vibrations by man over a period of 4 h are presented in Table 10.

TABLE 10. (FROM I. YA. BORSHEVSKIY, M. D. YEMEL'YANOV, S.S. MARKAR'YAN, V. B. TERENT'YEV)

Vibration group	Vibration frequency Hz	Vibration amplitude mm
Easily endured	10—30	Up to 0.8
	30—40	From 0.8 to 0,4
	40—60	Up to 0.4
Endured satisfactorily	Up to 10	From 0.8 to 1,6
	10—30	0.8—1.4
	40	0.4—1.2
	50	0,4—0.8
	60—70	Up to 0.4
Unbearable	10	Over 1,6
	20—40	" 1,2
	50	" 0.8
	60—70	" 0.4

The physiological action of vibrations on the human body appears mainly as general fatigue, in particular, because of the noise accompanying strong vibrations, and visual fatigue, because of observation of the shaking needles of instruments. Occupational illnesses are possible with the prolonged action of strong vibrations on the body [85]. /177

Vibrations show an unfavorable effect on pilot activities. During experimental flights in aircraft at an altitude of 30 m and a speed of 770 km/hr, a pronounced unfavorable action of the vibrations on pilot efficiency was noted. The pilots noted difficulty in control of the aircraft, especially in maintaining the heading, observing the instruments and charts and using switches. Also noted were the appearance of agitation and irritation during periods of strong and medium vibrations, and noticeable sluggishness, somnolence and the development of fatigue after completing the flight [93].

T. K. Isakov, D. I. Ivanov, I. G. Popov, N. M. Rudniy, P. P. Saksonov and Ye. M. Yuganov [47] note that vibrations creating movement of the entire body and shaking of the internal organs, at frequencies corresponding to the resonance frequencies of the different parts of the body, are particularly unfavorable for the operator.

The authors note that the resonance frequencies of oscillations are: for the entire human body, 4-6 Hz; for the heart, 5 Hz; for the head, 2-30 Hz; for the arms, 30-40 Hz; for the eyeballs, 60-90 Hz; and for the nervous system, 250 Hz.

A series of tests was carried out for the purpose of evaluation of the joint effect of linear accelerations and vibrations on different pilot reactions.

Data on the effect of these flight factors on the information capabilities of the operator and his efficiency are presented in Table 11.

Results of the tests showed that reduction in visual acuity is the most serious result of the action of vibrations. Vibrations with a frequency of 11 Hz, causing a 0.3 g and higher lateral G-force , as a consequence of deterioration in speech, rate of scanning space, visual acuity, capacity for tracking the operation of systems, absolutely reflect on the success of the flight and the safety of the crew. This is the conclusion which the investigators draw.

P. K. Isakov, D. I. Ivanov, I. G. Popov, H. M. Rudniy, P. P. Saksonov and Ye. M. Yuganov [47] show that protection from the adverse effects of vibration on the operator should be provided, /178

TABLE 11

Nature of work	Self-evaluation by operators of efficiency during vibration G-force levels (tolerance units)				
	0,14	0.30	0,53	1,36	1.65
Reading speed by needles (±2°/sec)	2	4	6	8	9
Reading by time counter	2	5	6	9	10
Reading by accelerometer	2	4	5	8	9
Switching off starting motor	1	2	3	4	6
Switching on reserve guidance system	1	2	3	4	6
Voice communications	1	3	4	7	9
Various engine cutoff, guidance and excess speed light signals	1	2	3	4	5
Operating toggle switches	3	4	6	8	9
Following air pressure in cabin, fuel cell and fuel tanks	2	4	5	8	9
Counting position errors at the moment of carrier startup	2	4	6	8	9
Quenching motion of carrier rocket	3	4	7	9	10
Total average evaluation	1,8	3,4	4,9	7,1	8,3

The numbers in the columns reflect the evaluation:
1 - normal; 2, 3 - negligible deterioration; 4, 5, 6, 7 - moderate deterioration; 8, 9, 10 - strong deterioration.

primarily, by a set of measures directed towards reduction in the magnitudes of vibrations of engines, mechanisms and devices, by improvement in the structural, technological and operational characteristics of aircraft.

CHAPTER V. PILOTED FLIGHT UNDER WEIGHTLESS CONDITIONS /179

In recent years, in connection with the successful development of astronautics and expansion of the manned spacecraft flight program, the interest of specialists in engineering psychology has grown noticeably in problems of the interaction of the operator with the technical devices of the control systems on spacecraft, under the unique and frequently unusual conditions of flight, not encountered in ground experience. The work of the operator in control of the craft and its systems during weightlessness or subgravity (partial weightlessness), during periods of orbital or interplanetary flight, has become especially important here. Partial weightlessness (1/6th g) will accompany man when he is on the lunar surface.

Weightlessness (not the disappearance of weight, but only the disappearance of the sensation of it) arises during free fall of a body, i.e., during that movement, when only the normal acceleration of gravity g acts on him.

This is observed during vertical ascent of a rocket (after the engine operation cutoff) and its descent (if the resistance of the atmosphere is ignored), during movement of a spacecraft in orbit, as well as during certain maneuvers in aircraft. Pilots have encountered the effects of almost complete weightlessness quite often when executing individual flight exercises, long before this problem became subject to careful study.

The weightless mode in an aircraft is characterized by zero G-force values on all three axes ($\Pi_x = \Pi_y = \Pi_z = 0$). Fig. 1.5 gives an idea of the production of the weightless mode in an aircraft.

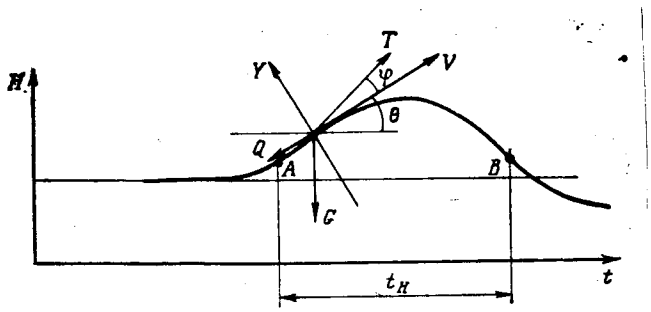

Fig. 1.5. Aircraft maneuvers during flight along the curve of weightlessness: G - weight; Q - resistance; T - thrust; V - velocity; θ - flight path angle of inclination.

From steady, straight-line flight, the pilot pitches the aircraft up with a given positive G-force Π_y. When the aircraft reaches the given pitch angle, by moving the control stick forward, the pilot decreases the positive G-force , bringing Π_y to zero by visual instrument. In this position, the aircraft continues movement along a flight path approximating a ballistic curve (parabola), with only this difference, that the /180

resistance is balanced by the projection of the thrust on the x axis (in the velocity system of coordinates), i.e., the G-force on the x axis (Π_x) also will be zero. The weight components along the x and y axes are balanced by inertial forces in the weightless mode. Passing through the altitude maximum, the aircraft begins to dive, gradually increasing (in absolute value) the negative pitch angle. Upon reaching the given pitch angle, the pilot brings the aircraft to horizontal flight by moving the control stick back. At this time, the weightless condition ceases, as a consequence of the appearance of positive G-force Π_y. The weightless mode continues in flight stage AB for a period of several seconds.

For thousands of years, the human body has been adapted to the conditions of existence on earth, where the gravitation level is 1 g. In space flights, he will have to experience the condition of subgravity (fractions of 1) or complete weightlessness.

Weightlessness is one of the most important, but nevertheless /181
insufficiently studied, problems of space medicine.

The complications of research connected with the action of zero gravity on the body is mainly that this condition cannot be completely simulated under laboratory conditions on earth, especially for a prolonged period of time.

It is natural that the value of such experiments is reduced.

From the psychophysiological point of view, there is an individual sensitivity in man to the phenomenon of weightlessness: in some, the condition of weightlessness causes a pleasant feeling, in the form of slight euphoria, and in others, on the other hand, complaints are manifested, illusions as to the position in space of the body arise, distinct symptoms of seasickness appear, which affect efficiency; in still others, almost no reaction to the unusual condition of the body is expressed.

During a period of weightlessness, the psychophysiological data on the position of the body in space is disrupted in man, as a result of disturbance of the sensory endings of the skin (higher sensitivity), for example, the skin of the soles of the feet in the standing position; the deep sensory endings, located in the muscles, tendons, joints (proprioceptive sense), internal organs (visceral sense); the vestibular apparatus and semicircular canals of the inner ear, from which the reflexes coordinating the statics of man in space issue, as well as the visual organs, which inform man of his position with relation to a given surface and play a supplementary role, if the other receptors are functioning normally.

Thus, in man, during a period of weightlessness, disappearance of the gravioreceptor function of various reflexogenic zones of the body, predominantly mechanoreceptors, baroreceptors, muscular sense and sense of space, sets in [95].

Under conditions of weightlessness, the functioning of the operator in following one or more indicators, determination of angular dimensions, angular velocities and distances under the unoriented conditions of space, identification of the shapes and /182
colors of objects when observing them, perception of sound signals and voice commands, are especially important. This requires study, in space flight, of such functions of the visual analyzer as accommodation, convergence, color vision and depth perception, the process of adaptation of the analyzers to change in gravitation and fusion processes.

Fairly extensive research has now been carried out on the condition of man under conditions of brief weightlessness (30-50 sec), during flight of an aircraft along a parabolic curve, as well as during the flights of the first spacecraft with a man aboard.

It has been established that the stay of a man under weightless conditions can be accompanied by vegetative disturbances. Prolonged weightlessness can lead to motion sickness, which, especially in the pronounced form of it, reduces the reliability of man as a "link" in the control system. Nausea and vomiting lead to a sharp suppression of the tonus of the nervous system, dysfunction of the analyzers and changes in the cardiovascular and respiratory functions of the human body. Vegetative disturbances and the motion sickness symptom complex are explained differently by different authors: in particular, by loss of weight of the otoliths, as a result of which a sharp reduction takes place in their inhibiting effect on the semicircular canals; accumulation phenomena during increase of Coriolis acceleration on the vestibular apparatus. Professor Ye. M. Yuganov and others [76] consider that weightlessness does not lead to functional switching off of the otolith apparatus, but is an unusual minus-stimulus for the otoliths. The motion sickness symptom complex can arise, not only by irritation of the vestibular apparatus, but by the flickering of various objects in the field of vision of the astronaut (opticokinetic irritation), as well as by displacement of the internal organs. According to the data of some authors, motion sickness symptoms appear even with irritation of the sensory nerve endings in the muscles, as well as by the conditioned reflex. However, a complicated vegetative-vestibular disturbance mechanism is most probable. The condition of prolonged weightlessness changes the settled systematic nature of the interrelationships and interactions of the analyzers (visual, vestibular, motor), which are firmly fixed under conditions of the constant gravita- /183
tional field of earth [79]. The accustomed visual stimuli, which

are necessary for orientation in space, are absent during a space flight. As a consequence of the change in nature of muscular activity, disturbance of the proprioceptive afferents is observed; conditions are created which increase vestibular sensitivity, while inhibiting effects on the vestibular apparatus are weakened or disappear [80]. Vestibular and opticokinetic stimuli can act on this background.

Thus, there is a disturbance of the interactions in the systematic nature of the analyzers, which leads to vegetative disorders, with motion sickness symptoms [49].

Under the brief effects of weightlessness, spatial position illusions frequently are observed in man. L. A. Kitayev-Smyk (1963) carried out observations of 193 pilots and parachutists, and he established that illusions are observed in only 25% of them. In 16% of the cases, a feeling of falling and collapsing, accompanied by fear, arose first, changing to a sensation of pleasant lightness, soaring, emotional excitement and joy, after some time. In 52% of the cases, the subjects did not feel the absence of terrestrial gravitation, but a change in its direction, i.e., they felt themselves to be lying on the chest, back, or side, etc. Illusions of this type continued for 25-80 sec, and they did not have such a pronounced emotional coloring as in the first case. In 7% of the cases, both illusions of falling and of turning over, accompanied by a considerable feeling of fear, with total disorientation in space, were observed. The spatial position illusions were expressed significantly less in persons having flight experience. The dynamics of the psychic and vegetative disturbances under the repeated influence of brief weightlessness demonstrated adaptation of man to the conditions of weightlessness. Thus, the psychic reactions disappeared after 5-20 times, and the vegetative ones, after 40-50. In this manner, an adaptive reaction quickly appears to brief weightlessness in man. Under conditions of prolonged space flight, weightlessness can have an adverse effect on the human body.

Professor A. M. Genin and I. D. Pestov have developed an /184
original diagram (Fig. 2.5), on which the basic types of disturbances, caused by the effects of prolonged weightlessness, and prophylactic measures for them are presented [16].

The visual analyzer of the operator is of particular value under conditions of prolonged weightlessness. The structures of spaceship manual control systems for accomplishing docking of spacecraft and landings on other planets, as a rule, are based on the abilities of man to detect light signals on one background or another and to identify different types of visual objects. Therefore, the importance of the level of the functional capabilities of astronaut vision is understandable.

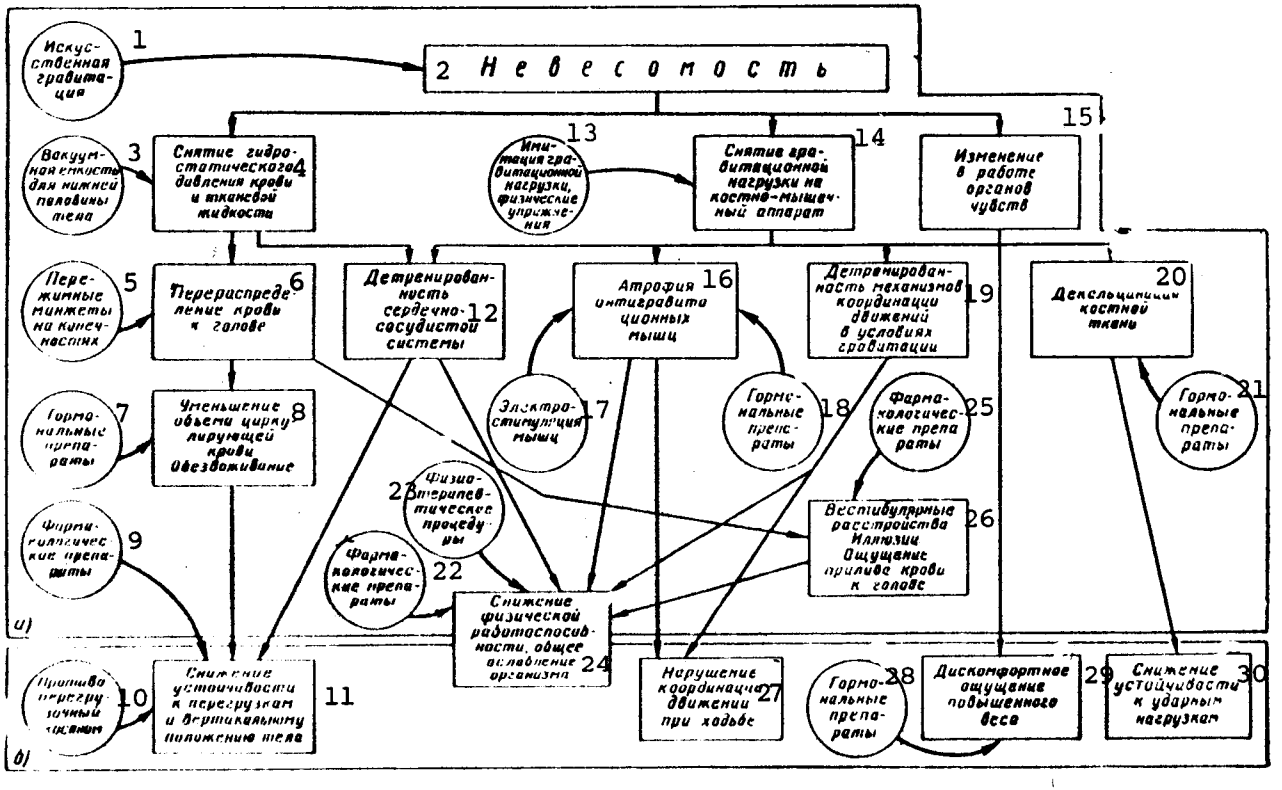

Fig. 2.5. Effect of weightlessness and prophylactic means (indicated by circles): a. during flight; b. in the postflight period (from A. M. Genin and I. D. Pestov).

Key: 1. Artificial gravity; 2. Weightlessness; 3. Vacuum container for lower half of body; 4. Removal of hydrodynamic pressure of blood and tissue fluids; 5. Survival cuffs on extremities; 6. Redistribution of blood to the head; 7. Hormonal preparations; 8. Decrease in volume of circulating blood. Dehydration; 9. Pharmacological preparations; 10. G-suit; 11. Reduction in resistance to G-forces and vertical position of the body; 12. Deconditioning of cardiovascular system; 13. Simulation of gravitational loading, physical exercises; 14. Removal of gravitational loading on skeletomuscular system; 15. Change in functioning of the sense organs; 16. Atrophy of antigravitation muscles;

[Continued on following page]

Key to Fig. 2.5 continued

17. Electrostimulation of muscles
18. Hormone preparations
19. Deconditioning of coordination mechanisms of movement under gravity conditions
20. Decalcification of bone tissues
21. Hormonal preparations
22. Pharmacological preparations
23. Pysiotherapeutic procedures
24. Reduction in physical efficiency, general weakness of the body
25. Pharmacological preparations
26. Vestibular disorders; illusions; sensation of blood rushing to head
27. Walking movement coordination disturbance
28. Hormonal preparations
29. Uncomfortable sensation of increased weight
30. Reduction in resistance to impact loads

In the opinions of some investigators [45, 68], visual acuity can be reduced under conditions of weightlessness. Thus, in experiments on 36 subjects during brief weightlessness, it was determined that visual acuity drops by 6%. Visual acuity does not undergo significant changes in space flight. Concerning operational visual efficiency, it is reduced by approximately 20-30% in astronauts in a spacecraft. In some cases, subjects under weightlessness observed the development of a violet halo around luminous objects.

Visual disturbances arising in the visual analyzers in a given case can be caused by change in the integrative processes in both the brain centers and on the periphery of the visual analyzers, in particular, by reduction in tonus of the individual eye muscles (lower, outer, rectus and ciliary muscles). Also, changes in color vision take place under weightless conditions [45, 68]. An increase in color perception, mainly of yellow and to a lesser extent of red, has been found in examination of color sensation in weightlessness. The brightness of green is increased only slightly, and blue hardly changes (L. A. Kitayev-Smyk, 1963).

The flight of the VOSKHOD-2 spacecraft permitted determination of a noticable reduction in subjective brightness of the colors examined by the astronauts. The average reduction in brightness in all colors exposed amounted to 26.1% in T. I. Belyayev and 25% in A. A. Leonov [4]. The greatest deviation was observed in perception of the brightness of purple and green (up to 50%) and the least to red. Reduction in brightness of the remaining sample /186

colors did not exceed 10%. The reason for such a significant reduction in brightness of individual colors under conditions of weightlessness still is not clear, and its explanation requires additional and more precise research.

The dynamic characteristics of the operator and his sensorimotor reaction times, under the influence of factors of brief (a day) space flight do not undergo serious changes (Fig. 3.5). In this case, the reaction of man to input signals having frequencies of more than 0.5 Hz prove to be the most subject to the effect of space flight factors. It also was determined in the flight that pain and tactile sensitivity, two-dimensional and stereognostic senses, as well as the ability to recognize objects by touch did not undergo noticeable change [4].

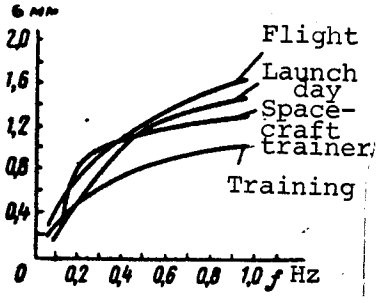

Fig. 3.5. Root mean spread in errors (σ) by A. A. Leonov to sinusoidal signals of various frequencies (f) (from P. I Belyayev, A. A. Leonov, V. A. Popov, L. S. Khachatur'yanets, V. K. Filosofov).

The state of neuromuscular coordination under conditions of weightlessness is of great practical importance, since the success of operator activities depends on his precision in execution of movements. Some of the investigators consider that movement coordination changes negligibly under conditions of brief weightlessness. According to the data of L. A. Kitayev-Smyk and A. T. Zverev [50], chronometry of complex movements, with participation of the muscles of the arms, legs and trunk, during manipulations of operators with a parachute suspension system showed that the time for putting on and taking off the parachute under weightless conditions is decreased by 20-25 and 30-35%, respectively (Fig. 4.5).

The operator (together with automatic machines) in spacecraft for various purposes will execute various sets of operations in control of the AC and its systems, under conditions of total or partial weightlessness. Among them are: steering the craft to accomplish its necessary orientation /187 and stabilization in a given direction; control of various research instruments; steering the craft during its approach to another spacecraft and during the process of docking them; control of corrections of the AC flight path and other things.

Besides, it should be considered that fairly complex life support systems should be used on future spacecraft , in the functioning of which (control, adjustment, monitoring) the astronaut-operator must play a great part, together with the automatic devices.

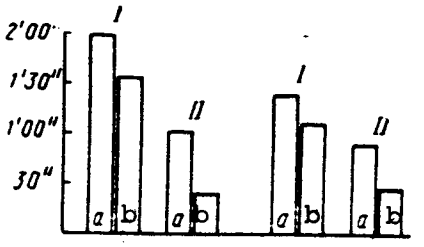

Fig. 4.5. Measurement of time for putting on (a) and taking off (b) parachute suspension system in natural gravity (I) and under weightlessness (II) (from L. A. Kitayev-Smyk and A. T. Zverev).

The concept of control of orientation of the craft in space includes, first, orientation and stabilization of the craft, i.e., execution of that program by which the housing of the craft will have a definite position (orientation) with respect to one reference point or another (for example, to the earth) and, second, change in orientation of the craft, its transition from one stabilized position to another.

Examination of spacecraft orientation control systems (Fig. 5.5) gives a basis for considering that, on the whole, psychophysiologically, this system differs greatly for the operator from the stabilization system of a modern aircraft [29]. These features and differences are that displays (optical reference points), which differ significantly from the well-known aircraft instruments (bank-and-pitch indicator and compass), are used in these systems. The structure of the orientation control system also has its peculiarities, and the work of the astronaut in control of orientation takes place under unusual conditions of total dynamic weightlessness. From the point of view of the dynamic characteristics of the craft orientation control system, it can be characterized as a control system with slowly proceeding processes, which puts the astronaut under unusual conditions, which, in distinction from conditions of a rigid limit or deficit in time, can be called conditions of a time "excess." /188

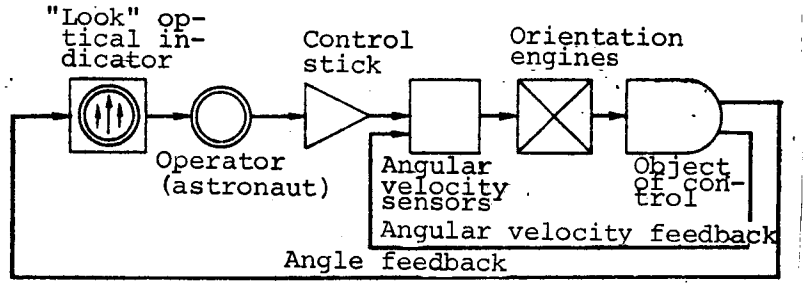

Fig. 5.5. Schematic block diagram of VOSTOK spacecraft manual orientation control.

The results of experimental research on the dependence of yaw perception time on angular velocity of movement of objects are presented in Fig. 6.5. These data give an idea of the possibility of identification of ground objects relative to the heading, at slow speeds of movement of the objects, through a "run" direction illuminator.

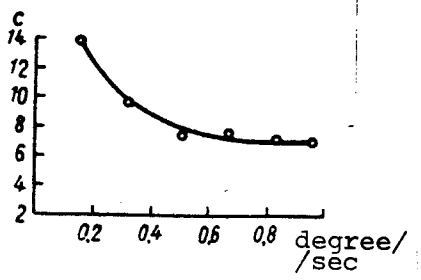

Fig. 6.5. Angle of yaw perception time vs. angular "run" velocity of objects.

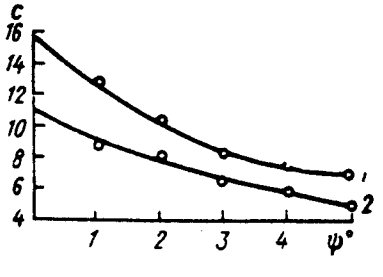

Fig. 7.5. Yaw angle perception time vs. its magnitude (1 - ω = 3.2 degree/sec; 2 - ω = 0.95 degree/ /sec).

It is evident from the graph that the time for perception of direction of movement decreases with increase in speed of movement of ground reference points.

The relationship of yaw angle perception time to magnitude of this deflection, at various angular velocities of movement ofobjects in the field of vision of the instrument, is shown in Fig. 7.5.

It is evident from the graph that perception time decreases with increase in the yaw angle, since, with increase in the angle between the run direction of objects and the longitudinal grid lines, at one and the same speed of movement, the velocity component perpendicular to the heading line increases, and movement distinguishable by the eye is accumulated in a shorter time. Experiments also have shown that, without restriction in the observation time, the precision of perception of the direction of movement of objects parallel to the heading line is practically independent of the speed of movement of the objects. The mean error in determination of run direction of objects relative to the heading line is not over 1°. Errors in determination of the yaw angle increase with decrease in speed of movement of the surface of the earth, if there is a time deficit. /189

Let us dwell briefly on the results of comparative investigations of certain craft orientation manual control systems with various controls [27, 30]. A three-channel contact control stick and a special keyboard were compared in the experiment.

The experiments showed that concentrated attention is required of the operator to hold the stick in the deflected position for a long time. Prolonged concentration of attention on holding the stick hampers accomplishment of the proper monitoring of instrument data and signal displays. As a result of arm fatigue and concentration of attention on holding the stick, spontaneous cutoffs and erroneous cut-inof control channels takes place. The process of control of angular movement changed noticably by use of a keyboard. The average values of the parameters characterizing the work of the operators with the aid of these controls are presented in Table 12.

The advantage of orientation control with the aid of a keyboard over control accomplished with the aid of the three-channel contact stick is evident from Table 12. In the case of key controls, the average orientation time, under identical initial conditions, is less, the energy consumption in execution of one and the same control task is reduced, the average number of erroneous orientation actions is decreased and skill in control with the system is more easily shaped. Besides, the use of the keyboard makes it possible to increase the discretion of the operator, to distribute attention more purposefully and, thereby, to reduce the mean time for perception of instrument readings while executing a control act, and it also makes it possible for the operator to digress (in case of necessity) for a short time to another type of activity (for example, to operate the radio switch and the like). /190

TABLE 12

Parameter name	Control by stick	Control by keyboard
Mean orientation time in relative units (in comparison with ideal control)	1.35	1.17
Mean value of generalized error in angular position in degrees	5.87	3.37
Mean energy expenditures in arbitrary units	15.4	11.9
Mean number of erroneous control actions in the process of one orientation cycle	3.0	0.05
Mean time for reading one indicator during the control process in sec	3.14	3.05

The slow flow of processes of control by individual systems in the AC ("excess" of time for the operator) and the necessity for continuous observation of the parameters monitored during periodic changes in them forces the use of the control system with a definite output signal constitution (structure, number). The control parameters, which should be reflected in the displays, so that the control system as a whole has the required technical characteristics and that the operator himself would be placed in a more favorable situation with respect to stress in his actions and speed of skill formation, were determined experimentally. /191

The investigations were carried out in a modelling test unit, in which the dynamics of the manual control process of an inertial object, with a discontinuous-type control pattern, were reproduced. A special three-coordinate handle and needle indicators were used for control. A monitoring system supplying the operator with mismatch signals and the first and second time derivatives of this mismatch were used the most successfully.

Comparative investigations of three display systems, differing in constitution of output signals (the so-called "total" system, "speed," and a system "with acceleration") showed that, in orientation time, magnitude of control errors and expenditure of reaction mass, the "total" display system should be given the preference; the system "with acceleration" turned out worst in these respects. By total number of errors by the operator, these systems are distributed in the same way (7.5, 7.8 and 20 errors, respectively, in 12 experimental tests).

It should be noted that, by use of the "with acceleration" display system, the capability of the operator to select the correct direction of movement of the handle and monitor its movement during the control process is limited, since a change in angular position of the object takes place comparatively slowly, and the angular velocity indicator gives data only during a small time interval. These circumstances led to the fact that the output characteristics of the system using the "with acceleration" indication proved to be below the corresponding characteristics, using the other two display systems.

In the course of reorganization of physiological functions in the work of the operators, using all three display systems, a regular tendency towards reduction in the bioelectric activity of the high-frequency cerebral cortex rhythms was noted, but no significant differences in degree of this reduction in use of the three systems was recorded. The electromyogram (EMG) readings /192
were higher during use of the "speed" system and "with acceleration" system than during similar work using the "total" display system. In dynamics of formation of operator skills in control of orientation, the "total" display system also has advantages over the other two [30].

Besides, the use of the "total" display system decreases the frequency of reference to control instruments without significant loss in data in the course of control.

Manual spacecraft orientation control systems, as a rule, have (for reasons of reaction mass economy) a low controlling action speed. Reactions to these actions take place with great delay. Experience shows that, for these cases, the information model must supply the operator with, not only the value of the monitored parameter, but the derivative of the mismatch. Sometimes,

this derivative can be "extracted" by the operator from a special mismatch indicator, the dial portion of which is made in a form convenient for determination of the derivative. Manual control quality, using five types of mismatch instruments, was determined:

normal needle type;

cathode ray tubes (CRT) with a luminescent parabolic segment, the base of which moved relative to the top of the parabola in proportion to the mismatch and corresponding to its sign, in which the length of the base was proportional to the mean root of mismatch, and the rate of increase in length of the base was proportional to the rate of change in mismatch and inversely proportional to the mean root of the mismatch;

CRT with a luminescent equilateral triangle, the base of which was displaced to the left or right relative to the apex by an amount proportional to the mismatch; the derivative of the mismatch was determined by the rate of change in area of the triangle, and also by the rate of displacement and increase in length of the base;

indicator with rectangular window, divided in two by a stationary vertical black stripe; at zero mismatch, a white triangle with a black horizontal stripe, forming a symmetrical cross with the vertical stripe, is seen in the window; the derivative of the mismatch was determined by the rate of change in area of the white surface in the right and left halves of the window, as well as by the rate of disturbance of symmetry of the cross; /193

a sound indicator, giving the operator data on the mismatch in the form of sound signals, furnished to the right or left ear, depending on the sign of the mismatch; the sound frequency changes with change in magnitude of the mismatch.

According to an integral estimate of the control quality, the CRT with indicator in the form of a parabolic segment proved to be the best one (0.85 arbitrary unit) and the one with the needle indicator, the poorest (0.59 arbitrary unit), although the mismatch was determined with extremely high accuracy (up to 0.005 arbitrary unit) from the needle indicator.

Experiments [34] have shown that the operator can estimate the value and sign of the mismatch, as well as the rate of change in it, with sufficient speed and accuracy from the characteristics of a graphic image (Fig. 8.5). Control of thecraft flight path can be required during long orbital or interplanetary space flights after precise definition of the location of the craft during navigational calculations, for accomplishment of the task of approaching space objects, moving along artificial earth satellite orbits, as well as for solving a number of other problems.

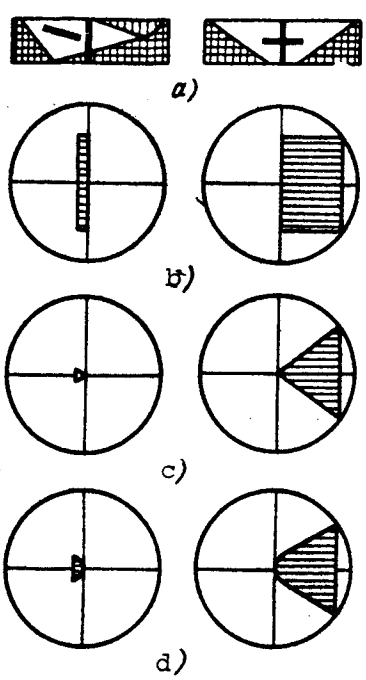

Fig. 8.5. Images of mismatch signal on indicators (from A. S. Yeliseyev, V. P. Popov, Yu. A. Rozanov, M. M. Sil'vestrov, T. V. Sazhinova); image area is proportional to magnitude of mismatch, and its position, to the sign (to the right - plus, to the left - minus): a. "cross on white background;" b. Rectangle fluorescing on cathode ray tube (CRT) screen; c. Triangle fluorescing on CRT screen; d. Parabolic segment fluorescing on CRT screen.

In all these cases, extensive maneuvering of the craft must be carried out.

A spacecraft maneuver is fundamentally different from an aircraft maneuver in the atmosphere. Thus, for example, the pitch angle of an aircraft must be increased for climbing, as a consequence of which the lifting force on the wings increases over its value during horizontal flight. To change the parameters of orbital flight of a spacecraft (decrease or increase of apogee and perigee), the shape of the orbit, it is necessary to apply a force to the craft (by means of correction engines), accelerating or slowing down its flight. In connection with this, maneuvers in space must be calculated beforehand. /194

In controlling a flight path correction of a spacecraft flight, the operator, using the information instruments, has to compare the actual craft position with the planned one, generate command signals and apply the necessary control actions to the craft through the controls, according to their magnitude and direction.

The system for control of the craft during correction of its flight path must be made in such a way that the craft control actions of the operator are reflected without delay on its indicators.

This permits a substantial increase in accuracy of control of the craft, which is of great importance for the flight conditions discussed.

Reading of visual observations of the surface of the earth by astronauts is of indisputable interest, from the point of view of explanation of the effect of prolonged weightlessness on the resolving power and other visual functions [11].

Analysis of data of observations of the surface of the earth and calculations of the visual acuity of the astronauts are presented in Table 13. /195

It is seen from the table that visual acuity under conditions of orbital flight exceeds the mean standards; however, this refers only to objects having linear extent (roads, contrails and the like).

TABLE 13

Objects observed	Approximate size of objects in angular min	Visual acuity
Rivers of the Amazon, Nile type	At least 20—25	Over 0.1—0.05
Highways	0.2—0.5	5—2
Ships in the roadstead	0.3—1.5	3—0.7
Ships sailing	1—3	1—0.3
Aircraft contrails	0.2—0.4	5—2.5
Beach strips	0.3—0.5	3—2

According to statements of foreign specialists, the results of observations of objects on the ground from space depend especially on the reflection coefficient of sunbeams (Table 14).

M. M. Kosenkov and A. P. Kuzminov [52] show that, during the flight of the spacecraft VOSTOK and VOSKHOD, the astronauts quite distinctly saw settlements, rivers, lakes, mountain chains, etc.

In the opinions of the authors, analysis of the results of experimental research gives the basis for asserting that objects having angular dimensions on the order of 10-15° can be seen from space by visual observation.

For solution of individual problems in research and study of space, the docking (assembly) of two or more spacecraft must be carried out, which K. E. Tsiolkovskiy pointed out in his time. Among such problems are: assembly of heavy orbital stations from individual units and segments sent into orbit by different carrier rockets; delivery of crews and necessary freight (supplies of food, /196 apparatus, instruments and other things) to orbital stations by transport craft; assembly, in near-earth, so-called assembly, orbit of space systems for accomplishing interplanetary flight and other tasks.

Docking of spacecraft is preceded by their approach maneuvers, when the controlled spacecraft, changing from its flight orbit to the orbit on which the other craft is moving, approaches it under the action of controlling forces, by a specified program. Many diverse means and methods of spacecraft docking have now

appeared in the literature, differing in basic principles of bringing the craft into contact. According to method of control, approach, mooring and docking of spacecraft can be accomplished automatically or semiautomatically with operator-astronaut participation, using manual systems for control of movement of the craft.

Direct contact of spacecraft is accomplished with the aid of docking units, providing mechanical capture, tightening and connection of electrical circuits. In the case of internal transfer, the docking unit should also guarantee airtightness in opening the hatch during flight of the craft in the docked position. In a particular case, the docking units can be a receiving device, in the form of a cone with a socket, installed in the target craft and the corresponding component, a rod with latches on the end, which is installed on the craft making the approach. /197

TABLE 14. (FROM MILLER)

Surface	Reflection coefficient
Ocean	3—5
Dry grass	3—5
Autumn forest	3—10
Earth	10—20
Rocks	30
Wet grass	15—25
New-fallen snow	70—81

According to data in the literature, numerous variants of approach and docking provide for two parts of the approach, distant approach, in which the craft being docked accomplishes maneuvers after its entry into orbit at a distance of 100-500 m from the target craft; close approach, in which the craft being docked maneuvers so that it takes a specified position relative to the docking device, and also receives the angular and approach speeds which permit contact with the target craft and subsequent coupling of the craft.

The operator must participate in the operation of the multicircuit system and provide for maneuvering of one craft relative to the other (each of which has 6 degrees of freedom), using a multipurpose indicator and manual controls and solving complex logical problems in this case. Rigid requirements for precision,

docking time and fuel consumption, and accomplishing them under conditions of weightlessness and high emotional stress, caused by the specifics of the control process and the crucial nature of the moment, indisputably leaves its print on the reliability of operation of the operator in the docking control system. Change in thrust efficiency of the correcting engines with decrease in relative distance and precision of transmission of the parameters measured to the operator close to their zero values play a large part in the general reliability and accuracy of the docking system. The unusual external lighting conditions also should not be discounted. The operator will observe a station with a brightness of $2.4 \cdot 10^5$ nit on the black background of the starry sky, on the background of the moon (with a brightness of $3 \cdot 10^3$ nit), as well as on the background of the earth, illuminated by the sun (having a mean brightness value of $1.3 \cdot 10^4$ nit).

The main requirements for the docking system are: minimum expenditure of reaction mass for accomplishment of a series of maneuvers by the docking units and minimum time in maneuver and docking. These requirements frequently contradict one another, and, in case of necessity, they must be satisfied by a reasonable compromise.

In all cases, it is considered that the docking units must /198
be sent up from earth to a close distance, in orbit, generally not coplanar, for example, the approach of the Gemini spacecraft to the Agena rocket (Fig. 9.5). Ground control systems then provide generation and transmission of commands for executing the approach of the units (let us call one of them the craft, the one containing the crew, and the other the station) to a distance of 30-50 km, guaranteeing positive operation of the onboard automatic craft-station approach systems to the distance of the action range of the docking systems, operating with operator participation on the approach portion. It is considered established that the second portion of the approach begins at a distance of several hundred meters (up to 1000 m). A special onboard guidance system provides for detection and guidance of the docking units in the field of view of a television docking device, intended for observation of items of the assembly from the docking platform within a narrow solid angle, at comparatively great distances and within a broader solid angle at close distances. The television /199
device can give the operator data on the mutual positions of the craft and station and make it possible to estimate the distance between them and determine the relative angular positions, as well as to monitor the quality and reliability of the docking itself. A special optical sight can be used for docking in place of the television device (or supplementing it). In all cases, optical reference point-indexes should be installed on the units being assembled and their observation by the operator under various conditions of illumination, including the shadow of the earth should be guaranteed (by means of devices, for example, of special biased lighting projectors). These reference points are necessary

for guaranteeing control of the mutual orientations of the docking units (angular positions). It is difficult to determine the bank, pitch and yaw angles by observation of the external outlines of the units. Therefore, the necessity for special identification devices, for example, on the station, is obvious. They can be, in particular, black-white rings, applied to the conical surfaces, the images of which will be distinctly visible in the field of view of the operator instrument, in the form of concentric circles in the oriented positions of the unit. With angular dimensions of the identification devices of no more than 10 min, the position angles of the station and its stationing in the oriented position can be determined with an accuracy of 3-5°.

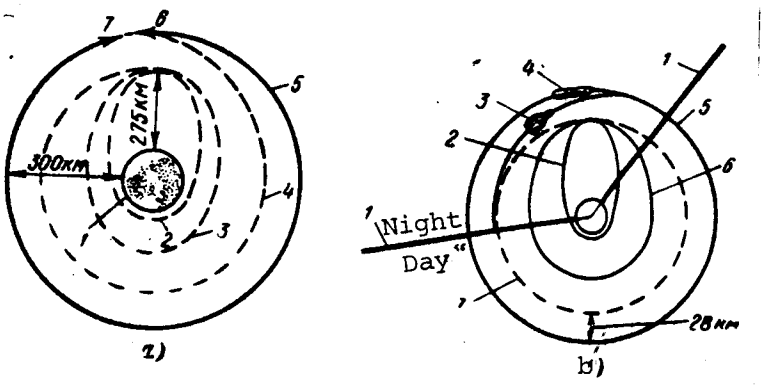

Fig. 9.5. Schematic diagram of encounter maneuvers in orbit: a - general diagram of encounter maneuvers in orbit: 1. spacecraft launch point; 2. initial orbit of spacecraft; 3. first transition orbit of craft; 4. second transition orbit of craft; 5. orbit of spacecraft; b - diagram of encounter maneuvers in orbit and docking with carrier rocket: 1. day-night boundary 2. initial orbit of craft; 3. spacecraft; 4. carrier rocket; 5. circular orbit of rocket; 6. first transition orbit for encounter; 7. second transition orbit for encounter.

The rate of approach of the units in the last portion before docking should not be greater than a few meters per second (its magnitude will determine the approach time, which must not be too great). With decrease in the relative distances to zero, the relative speed should be decreased to a minimum value, guaranteeing an unstressed coupling of the craft and station, but, at the same time, sufficient for triggering the latches. At the moment of docking, when the relative distance is close to zero, the relative angular position of the craft and station should be completely determined, and the relative angular velocities should not exceed the calculated values.

Let us examine two methods of approach. In the first method, the station does not have maneuverability, and the craft, with its crew, maneuvers relative to the station. In the second method, both craft and station can carry out a maneuver upon command of the operator from the craft. In the first method of encounter, which we use more often in the approach stage, the /200

operator must control the maneuvering ship in such a manner as to provide direction of the thrust vector along the "craft-station" line of sight. To control the position of the craft and to turn the thrust vector in the necessary direction, a rotational jet control can be used. The operator can use a two-degree stick (control of pitch and bank) and pedals (like in an aircraft, for control of yaw) as craft position controls, and for control of the longitudinal thrust, a throttle, with buttons for switching on the pulse and continuous action thrust modes. In addition, the operator, in proportion to nearness to the station, should switch over the scale of the relative distance indicator and relative rate of approach indicator for more efficient use of the instruments over a wide range of change in these measurable parameters.

Information on the distance and rate of approach of the craft and station, on the angles determining the positions and on the angular velocities of the craft are necessary to the operator for exercising control during the approach and docking. The operator, knowing the direction of the line of sight and the distance to the station, directs the encounter process: by means of turning the craft, he establishes approximately the necessary encounter heading and subsequently reduces the speed of the craft relative to the station to zero.

One of the main psychophysiological features of control in this method of approach (at relatively great distances between the craft and station) is the negligible angular velocities of the line of sight. A comparatively difficult task in control of a slowly proceeding process faces the operator here. After the encounter course is set, the assigned position of the craft should be maintained, since, due to the curvature of the orbit with respect to the system of coordinates selected, the craft will deviate from the previously established direction. The second part of the task of the operator is accomplishing braking, for the purpose of decreasing the relative speed.

In the second method of approach, the operator controls the craft and station, as well as movement of the center of mass of /201
the craft and station in three coordinates, by angular movements. The parallel approach method can be used here, in which the angular velocity of the line of sight is maintained in the zero position. Quenching of the angular velocity of the line of sight to zero or to a minimum value is accomplished by means of application of force (to the craft or station), perpendicular to the line of sight. When using one engine for center of mass movement control, the axis of this engine is oriented perpendicular to the line of sight and parallel to the lateral speed. It operates until the angular velocity of the line of sight is equal to or close to zero. It is not efficient to change the speed in the final portion of the approach by this method of control of the movement of the center of mass, since the docking must

take place at a specified relative angular position of the craft and station, and as a consequence of the fact that the line of sight will drift from the station at a close distance (owing to Coriolis forces). To compensate for this drift, very frequent correcting pulses, perpendicular to the line of sight, the accomplishment of which is difficult, are necessary. This method can be used in the distant approach portion. In the case of use of three engines for control of movement of the center of mass, which is profitable in the final portion of the approach, one engine (longitudinal) is established along the line of sight and the other two (lateral), perpendicular to the line of sight. The longitudinal engine provides for decrease in the relative distance by an appropriate program; the lateral engines provide for decrease of the angular velocity of the line of sight to zero.

As a result of research carried out abroad, display system requirements and basic assumptions were developed, from which one should proceed in building displays of the manual control system for the final portion of the approach of a spacecraft to the station (target) and in establishing the sequence of operations carried out by the cosmonaut in the process of accomplishing the encounter, by use of these displays [21].

After acquiring the target (in the portion from 80 km to 15 m), the display system should permit the operator to determine the relative velocity vector in a coordinate system, the origin of which coincides with the center of mass of the target and one of the axes is directed along the local vertical. The display system proposed by the foreign specialists consists of an onboard radar azimuth and position angle display, three-degree orientation indicator, angular velocity displays on each of the three axes of rotation of the craft, a tape indicator of the "distance-rate of approach" and a vector encounter display. An approach vector display is shown schematically in Fig. 10.5. The AC is represented in the center of the vector diagram; the open circle corresponds to the end of the actual relative velocity vector and the filled circle to the end of the required velocity vector. Correction of the required velocity vector coincides with the target line of sight. The angle between the AC longitudinal axis and the required velocity vector is the pitch angle to which the craft must turn in order to direct the axis of its main power plant to the target. /202 /203

The indicated necessary speed value is determined by the adopted guidance method for experimental conditions, and the required speed value was equated to the square root of the distance. The true speed value, indicated on the display, is equated to the ratio of the actual speed to that required.

During the approach, the operator must determine the capture moment of the target by the onboard radar display, yaw the craft

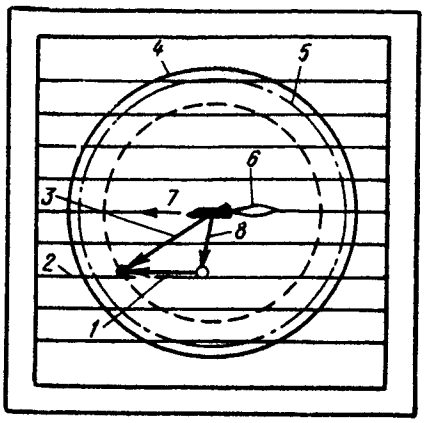

Fig. 10.5. Vector approach indicator (the ● and o symbols are displaced; all remaining images are stationary): 1. necessary velocity increment vector; 2. grid for facilitating orientation of thrust of main power plant (PP); 3. necessary relative velocity vector; 4. main PP thrust limit; 5. vernier engine thrust limit; 6. main PP indicator; 7. aircraft acceleration direction; 8. true relative velocity vector.

until its longitudinal axis coincides with the approach plane, and bank the craft until the target is in the pitch plane [29].

Then, using the vector display, the craft is pitched until the moment when the line of action of the main power plant thrust becomes parallel to the line connecting the ends of the two vectors on the display and when the actual relative velocity vector and the required vector are gradually superimposed on one another (on the display). If the actual velocity vector value exceeds the safety level, corresponding to the limiting thrust value indicated on the vector display, the thrust vector must be made to coincide with the direction of the actual velocity vector, to accomplish a partial braking. When no more than 1.5 km remains to the target, the operator must switch over control from the main power plant to the vertical engines (on all three axes) and turn the craft 180° (by pitch angle).

In the docking portion (from a distance of 15 m until the moment of contact), the operator should use only visual data.

Simulated approach maneuvers were carried out at an orbital altitude of 565 km and were begun from a distance of 80 km, with an initial lateral displacement of ±15° and vertical displacements of 0, ±20, ±45 and ±70°. The initial relative speed was 245 and 123 m/sec. During the simulation, a three-degree flight path control stick, a button for fixing the orientation on each axis, a main engine on-off button and two control sticks for longitudinal displacements, with the aid of orientation jet nozzles situated /204 in pairs (during operation, inconvenience was noted in the automatic engine thrust cutoff in the final portion) were used.

Fifteen experienced pilots took part in the simulation and 260 experiments were carried out in all. All pilots (except for one) could execute the approach from the first attempt (at a distance of 15 m from the target, the approach rate was 2 m/sec). The pilots could execute an approach to 1.8 m from the target and even closer, during which the rate of approach was decreased by them to zero or some given small value. Seven pilots (of 15) not

only successfully executed the maneuver on the first attempt, but did not lose the target a single time during the maneuver. One-fifth of all experiments were connected with efforts to execute the approach in a minimum time, for which the craft was accelerated initially to a specified approach rate, and then braking was carried out to the very end of the maneuver.

After the experiments, the pilots noted that the use of the display system facilitates full understanding of the flight situation and is completely adequate for executing any assigned maneuver in the approach to the target.

Results of a simulation experiment have been presented in the foreign press [25], on accomplishment of longitudinal control by the operator (change in distance and pitch angle during docking of craft in 370 km altitude coplanar orbits). Six operators took part in the research. It was assumed that the craft which the operator was located was stabilized relative to the vertical in pitch, bank and yaw angle. Two systems were investigated. The first "pitch-thrust" system provided one rectilinear movement (back-forward) and one rotation (counterclockwise and clockwise). The second "orthogonal" system provided forward-back and up-down movements. Two control sticks were provided for both systems, in which they could be displaced by ±45° from the center position with a force of 450 g. In the first system, the movement of the left stick (forward-back) imparted an acceleration to the craft, the value of which was proportional to displacement /205
of the stick (the extreme position corresponded to an acceleration of 0.9 m/sec^2). With the aid of the right stick, the craft was displaced downward or forward (by forward movement of the stick) and up or down (by backward movement of the stick). The extreme position corresponded to a rate of change in pitch angle of 3°/sec.

In the second system, a two-way vertical thrust was created with the right stick. The flight altitude was increased by turning the stick and decreased by moving it down. Vertical accelerations were proportional to the angle of displacement of the stick (at maximum displacement, they were 0.9 m/sec^2).

The satellite to which the craft moored was presented on the oscilloscope of the display in the form of two concentric circles: the outer one corresponded to the external dimensions of the spherical satellite (its diameter, 46 m) and its inner to the mooring dimension (1.2 m). If the operator was at a distance of 55 cm from the screen, the angular dimension of the circle corresponded to the angular dimension of the actual target. The angle of observation amounted to 23°. A rectilinear coordinate grid, with 2.5 mm divisions, was applied to the screen. If the operator raised his craft upward, the target dropped downward; if the craft dropped down, the target rose. The inner circle increased

in diameter with approach of the craft to the target, reaching maximum size at the time of docking.

The main task of the operator was to guide the craft on the approach to the satellite; in this case, a moderate fuel expenditure and smooth impact on the target was achieved.

The results of the research are presented in Table 15.

TABLE 15

Parameter name	System type	
	First system	Second system
Number of approach attempts by each operator	72	72
Number of successful approaches	46	72
Relative time for accomplishment of approach maneuver	1 1	0.64 0.64
Successful approaches from initial positions with distance of (%)		
610 m	80	100
1520 m	60	100
1830 m	47	100
2440 m	47	100
Mean impact speed in mooring (m/sec)	2.4 (in 35 attempts)	1.4 (in 60 attempts)
Average value of time used for approach (relative units)	0.023	0.015
Fuel consumption as a function of initial position (relative units)	0.0019-0.0011	0.0033-0.0007
Control effectiveness criterion (relative units)	2950-8333	875-8772

On the basis of the experimental data, the preference was given to the orthogonal approach and docking system, and it was noted that, despite some irregularities in the displays, brief

dockings in coplanar orbits were successfully carried out by the test subjects.

The time available to the operator during work on the final stage of the approach was 5-6 min. The tasks of the operators, under the unusual conditions of weightlessness, in bringing the craft and station together were new and exceptionally complicated. They are many times more complicated than the most difficult tasks of aircraft crews during flight in close formation or while executing aerial refueling. Experience in docking spacecraft with /206
operator participation (in flight and in simulation units) shows that the operator sufficiently successfully (with specified training) copes with the problems posed for him (in time, accuracy and fuel consumption). Operator overloads of information, coming in from many control channels, can cause abrupt shifts in operator activity, reducing reliability of operation. Missing of incoming signals and late reactions to the complicated situation may appear, with these signal misses being in logarithmic proportion to the rate at which signals come to the operator. Considering the same exceptional emotional stress on operator activity, due to the extremely crucial nature of execution of the /207
tasks, the work of the operator in the approach and docking control system should be considered very complicated and difficult, requiring mobilization of all his psychophysiological capabilities.

A series of investigations has been carried out in recent years and is being carried out now to search out methods of maintaining normal activity and efficiency of man in prolonged space flights under conditions of weightlessness.

Among these methods are:

fixing the operator in the working position and providing him with satisfactory movement;

the use of drugs having a tonic effect on the human body;

the use of physical exercises and massage for maintaining muscle and vessel tonus;

creation of an artificial force of gravity.

The last method is the most radical one. Solution of the problem of the advisability of creating artificial gravitation depends greatly on how man withstands tests, in which it is proposed to subject him to the prolonged effects of weightlessness.

These conditions are characterized,first, by the fact that, since the artificial force of gravity will be created by rotation of the craft around one of the inertial axes, the magnitude of the

centripetal force of inertia determines the level of the artificial gravity. Besides, Coriolis inertial forces [87] will act on a man during his movements about the cabin, as well as during movements of the head and extremities. A diagram of the Coriolis acceleration in a rotating spacecraft, the magnitude of the Coriolis acceleration and the magnitude of the artificial gravity are presented in Figs. 11.5, 12.5 and 13.5 [87].

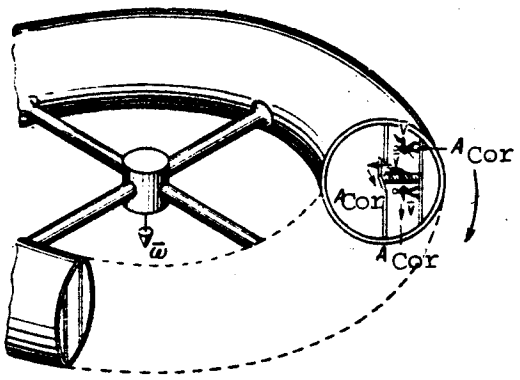

Fig. 11.5. Diagram of Coriolis acceleration in rotating spacecraft

Analysis of the effect of human capabilities on the choice of structural parameters of a spacecraft in which artificial gravity is created by rotation, shows that:

The upper limit of the angular velocity of rotation should not exceed 0.4/sec. In this case, the value of the artificial gravity should not be more than 0.9 g; the lower limit of the artificial gravity is less than 0.2 g;

In optimum configuration of the spacecraft, the cabin should have the shape of a cylinder, located parallel to the axis of rotation and another symmetrically located cylinder should serve as a counterweight; for creation of a 0.9 g gravity, the radius of rotation of the spacecraft should be 60 m at ω = 0.4/sec. /208

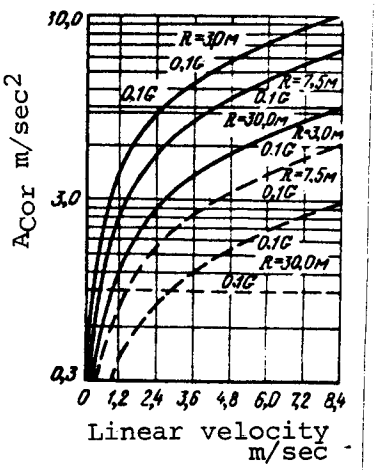

Fig. 12.5. Magnitudes of Coriolis acceleration vs. rate of linear displacement of man.

On space flights, Soviet astronauts fastened in seats, under conditions of weightlessness, successfully carried out a series of important functions, connected with control of the craft and also made entries in the log, and did movie photography and other operations. Determination of control capabilities in free "flight" was unsuccessful.

The problem of how long flights, for example, for the purpose of mastering the nearest planets, Mars and Venus, must be prepared for are extremely complicated and remain far from clear. They will take several years at contemporary speeds. Must the body of the astronaut be maintained at the "ground" level? Continual use of drugs, continual stimulation of the nerve and muscular systems also will scarcely be justified.

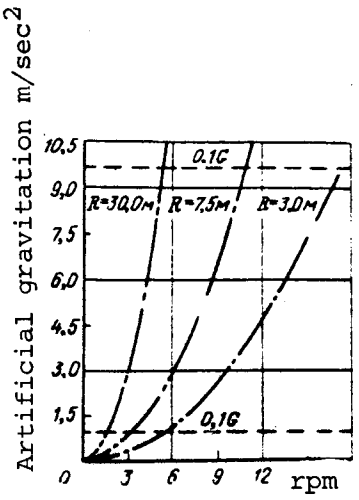

Fig. 13.5. Magnitude of artificial gravity vs. radius and rotation rate of craft.

The use of certain drugs can be imagined, which prevent the loss of water and mineral salts from the body. Undoubtedly, this requires the development of a special motor regime in flight, calculated on the load of the muscular apparatus and cardiovascular system. /209

It should be noted in concluding the chapter that the prolonged effect of subgravity and weightless conditions on man still has not been studied sufficiently.

The most radical means of study of a prolonged action of weightlessness on the human body is the creation of orbital manned stations, which should permit research to be carried out on groups, tested over a long period of time.

CHAPTER VI. MAN-MACHINE SYSTEM IN UNSUPPORTED AND UNORIENTED SPACE /210

The first successful manned flights in space, with the execution of experiments on man leaving a craft into open space presented science and, in particular, specialists in the field of engineering psychology in aviation and astronautics with a completely new problem. Its essence is in the study of specific aspects of the biomechanical man-machine system, under conditions of action by the operator in unsupported and unoriented space. The specifics of this include, not so much the fact that the operator finds himself under completely unaccustomed conditions upon going out into open space, as in the fact that, for carrying out various tasks in orbital flight, he himself is turned into an object of control, in simultaneously carrying out the functions of receiving and processing data and transmitting control commands. Under these conditions, it is obvious that the general problem of interaction of the operator with the machine is subordinated to a new higher degree, and that solution of it, undoubtedly, is complicated.

The operator must go out into open space to carry out examination and external repair of the craft, work with scientific equipment, the dimensions of which do not permit its use within the craft, conduct assembly work in orbit, and transfer from craft to craft in giving help to crews of other craft or in interaction with them for purposes of carrying out various scientific investigations. For this, in all cases, the operator has to /211 move and act precisely, rapidly and purposefully.

Upon going out into space, the man himself becomes an "artificial satellite" of his craft. At this moment, additional difficulties arise in operation of the regulating mechanisms, providing normal activity for various units and systems. Knowledge in this field remains limited up to now and requires detailed investigations.

Under the conditions of open space, weightlessness sets in in a new aspect for the investigators and operators -- the phenomenon of unsupported space [92]. A small external force or movement can cause rotation of the body of the astronaut-operator in various planes, with quite high angular velocities, and, thereby, an increase in magnitude of vestibular stimulation, and disorganization of purposeful actions.

It is well known that coordinated movement is basic to any purposeful activity. However, both changes in mechanical conditions (absence of weight with conservation of mass and, consequently, inertia) and the afferent nerves, changing the corrections to movement on the feedback principle, have an effect on coordination of movement.

Under conditions of weightlessness, the regulating and posotonic reflexes, on the background of which motor coordination of man is built, change completely. Moreover, free outer space is unsupported space and there are no support points in it, which creates completely new, unusual conditions for biomechanics.

Which of the sense organs takes the leading role in correct spatial orientation under conditions of weightlessness?

The signaling system of the cutaneomechanical sense organs and the articulomuscular ones, the proprioceptive ones, the sensory part of which is imbedded in the muscles and joints, are of great importance in spatial orientation [41, 71].

In analysis of the spatial relations between the sensory organs in the weightless state, other relations than under terrestrial conditions arise. In this case, vision, cutaneous, and articulomuscular sensations and, to a lesser extent, the vestibular apparatus signaling system, take the main role. /212

At first glance, this is not strange, but the greatest disruption is caused in the signal system of the vestibular analyzer, the leading sense organ in analysis of spatial relations under terrestrial conditions. This has been confirmed by the research of many scientists [49, 76, 79].

Spatial orientation in weightlessness is not stable. Illusions can always arise and motor coordination can be disturbed. Nevertheless, with the aid of careful selection and special methods of training, man is successfully prepared for not having his spatial orientation disturbed under weightless conditions.

The absence of support in free flight in space still does not mean the disappearance of support reflexes. Overcoming these protective reflexes requires great effort of the astronaut.

If a man is set on a rocking plane in a special experiment, the response will be expressed by increasing general muscular stress, especially in the muscles of the legs and body, which directly participate in the "play" of maintaining equilibrium.

It is well known that the reaction of a pilot to the sensation of falling or instability is expressed by "gripping the control stick." This is the prehensile reflex. If, in an experiment, a man is given the possibility of not only balancing on an unsteady support, but of "damping" his oscillations with the aid of the hands, the squeezing of the hands increases in proportion to increase in "unsteadiness."

Guaranteeing the operator the necessary mobility is a big problem under the conditions of open space, since the total vacuum

of space and the peculiarities of the temperature conditions require the use of a space suit of fairly complicated construction by the operator [40]. The space within the space suit should be provided with an increased oxygen pressure, on the order of 0.3-0.4 kg/cm^2. A space suit generally reduces the mobility of the joints of the arms and legs of the operator, who accomplishes movement control with great difficulty, and a man quickly becomes fatigued while working. For example, when the American astronaut E. Cernan went out of the Gemini-9 spacecraft, even during execution of the simplest movements in the space suit, the pulse reached 180 beats per minute. The increase in efforts of the astronaut, directed towards maintenance of orientation in space, was accompanied by an increase in his muscular activity, which leads to strong emission of heat and, thereby, complicates the task of heat removal. This requires powerful heat regulation means and complicates the construction of the protective space suit. /213

The angle of view in modern space suits is restricted and amounts to 120-150° in the vertical plane and reaches 170° in the horizontal plane. This circumstance, together with the possibility of moisture condensation on the helmet face piece (which, by the way, developed with astronaut Cernan) impairs the capabilities of the operator for visual observation of objects in space. Moreover, it should be taken into account that the presence of sharp contrast of the object of observation -- one part, turned towards the sun, is brightly illuminated (two times brighter than on earth), and the other, in shadow, is completely dark, greatly hinders observation in space [13, 40].

The spectral composition of the solar radiation to which the vision of man is adapted is considerably different from that which he encounters in space. This is explained by the fact that the terrestrial atmosphere serves as a unique filter, changing the initial solar spectrum. Therefore, the radiation of the sun beyond the limits of the terrestrial atmosphere cannot be considered safe for perception by the unprotected eyes. Calculations show that, at a height of 50 km, the action of radiation on the eyes over a period of a minute can prove to be sufficient to irreversibly injure vision.

Therefore, the eyes must be protected by optical filters, which would reduce the spectral distribution and intensity of the extra-atmospheric radiation of the sun to the terrestrial level.

It is most convenient to make the protective filter of two sequentially installed filters. One, discriminative or selective, reduces the initially incident radiation to the spectral composition of solar radiation, similar to that "filtered out" by the terrestrial atmosphere (with perpendicular incidence of the solar /214

rays). The second, a gray filter, restricts the total intensity of the light flux to permissible standards for the eyes. The light intensity which is absorbed by the eyes under natural, terrestrial observation conditions, corresponding to the mean daily illumination of the terrestrial landscape, is taken as the standard. In this manner, optimum visibility and safety of observation conditions can be created by two filters [13, 40].

Brightness and illumination of reference points in space also are determined with great difficulty. Because of the absence of an atmosphere, visual observations in space will be carried out on a background having an extremely great contrast. If an observed spacecraft is close to earth, its illumination conditions also will change sharply, depending on whether it is in a region illuminated by the sun or in the shadow of the earth.

Exchange of information between operators in open space and operators in a craft interacting with them also can be hampered, although the necessity for guaranteeing high accuracy of work in open space, requiring the expenditure of great effort, coupled with the danger and risk, requires reliable communication systems.

Foreign scientists propose the creation of a special device for these purposes, capable of memory storage of the sequence of work, individual operations, and of rapid and exact calculation of effort and time, as well as of warning of danger in case of necessity [25, 29, 57].

The problem connected with selection of control levers used by the operator in unsupported space should not be narrowed down.

A series of experiments has been carried out, concerning the capabilities of an operator to execute various types of activities in a space flight. The effectiveness of the use of levers under conditions of the absence of friction was investigated. Experiments were carried out with minimum friction of the support on which the subject was located (coefficient of friction 0.0015). Backward and forward movement of a lever proved to be almost /215
impossible with negligible friction. Maximum effort was required to move the lever, while the subject simultaneously stabilized himself. The efficiency of the forces applied by the operator, compared with the efficiency of a man operating under normal conditions, decreased sharply. It was 1/27 during movement back, 1/18 during movement forward and 1/3 during rotational movments. The magnitude of the effort in compressing and stretching with both arms did not change significantly.

Problems connected with providing the astronaut with a special instrument and choice of methods of work under conditions of weightlessness are of great importance.

A tool for work by an astronaut should be simple, guaranteeing quick and easy use of it in assembly and repair, and it should not create moments acting on the astronaut. The number of tools should be the minimum possible. A set of spare parts and materials is necessary, depending on the operations carried out.

Foreign specialists have developed a universal tool for use in open space. The weight of the tool is 3.6 kg. The handle is constructed so that it is convenient to hold it with a gloved hand. Exchangeable attachments permit the use of this combined tool as a monkey wrench, screwdriver, drill and so on [25, 29, 57].

The primary distinctive feature of the tool is a very small reaction torque ($7.2 \cdot 10^{-4}$ kg-m). This is achieved by the fact that, simultaneously with rotation of the shaft in one direction, a barrel, equipped with universal clamps, rotates in the other direction (through a special ball reducer), but with considerably greater speed. In this case, a nut is tightened in 3 sec. The tool makes it possible for the operator to work with the arms in an unstable position relative to the joint being tightened and with the misalignments which arise. A special screwdriver tip shape ("swallowtail" type) was built for this, combined with a special screw slot.

The magnitudes of the forces which can be applied by a floating operator under weightless conditions, presented in foreign literature, are indicated in Table 16. Attention is drawn to the /216 fact that these forces (with the exception of compressing and stretching with both arms) are comparatively small and inadequate for accomplishing, in particular, assembly work connected with attachment and tightening of the joints of parts, assembly of piping and other things.

TABLE 16

Type of force	Mean magnitude of force with friction	Mean magnitude of force without friction
Longitudinal displacement by pushing	33 kgf	1 kgf
Longitudinal displacement by pulling	27.5 kgf	0.5 kgf
Rotation by pushing	7 kgf·m	4 kgf·m
Compression	46 kgf	45 kgf
Stretching	42 kgf	41.5 kgf

An essential condition for executing precise, coordinated movements and proportioned muscular efforts is the presence of a support (fastening belt, arm and footrests).

In carrying out repair and other work in open space, it is most difficult for the astronaut to achieve stable equilibrium on the outer surface of the spaceship. Even if the astronaut uses tools with small torques and low impact energy, just the same, with one touch on the skin of the spaceship, he can be driven back to a considerable distance.

One foreign firm proposed building a special device, swivelling at various angles and holding the astronaut to the skin of the ship. Using this device, the astronaut can work with both hands. The equipment is a tripod, the upper part of which envelops the back of the astronaut, and legs, with ball joints which adhere firmly to the outer hull of the craft. The device is undergoing intensive ground tests in space simulators, and its capabilities under conditions of sharp temperature and pressure drops are being studied [25, 83]. /217

The results of research, carried out by D. Adamson [1], under conditions simulating space, are given in Table 17.

TABLE 17. TIME (MIN) SPENT IN PERFORMING WORK OPERATIONS IN VARIOUS OUTFITS

Work operation	Test conditions				
	Light suit	Space suit w/o pressure	Space suit under pressure using individual capsules		
			Using air-tight sleeves	With hatch at 90° angle	With hatch at 45° angle
Washer replacement	19.9	38.5	Not done	86.8	90.00
Panel replacement after meteor puncture	6.1	5.5	7.55	7.2	6.55
Fuel cell replacement	14.8	19.4	48.00	49.4	37.40
Replacement of damaged switch	8.6	10.3	34.40	26.5	22.70

The subject worked in three situations in a space suit: through the open hatch in a capsule, when the joint plane forms an angle of 90° and 45° with the vertical and in a capsule

without a hatch, equipped with airtight cloth sleeves of bellows construction (Fig. 1.6).

As a result of the research, it was determined that, to provide for normal work by the operator, his individual capsule should have an inspection window, covering part of the chest, for improvement of the downward view, but that it should not go beyond the radius of the helmet. The airtight sleeves should enclose the arms snugly below the elbows. The apertures in the capsule for the arms should be located at an angle to each other. For freedom of movement of the shoulder joint, a flexible bellows connection must be used. The capsule should have a capability of accomplishing linear movements and turns. /218

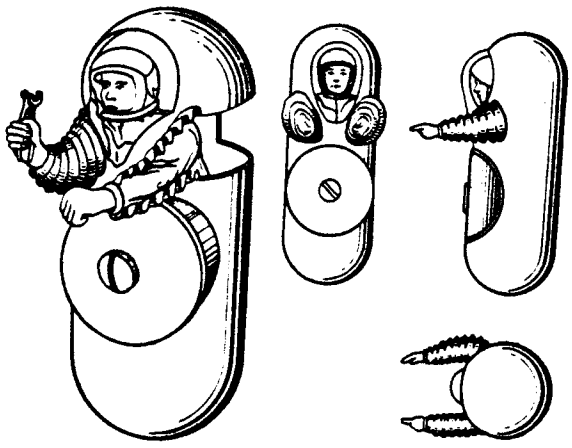

Fig. 1.6. General view of capsule with airtight bellows sleeves.

It was determined that considerable improvement is required in the standard gloves, in order that they can provide a fine touch, ease of movement of the fingers and the possibility of "approach" to almost inaccessible sections.

At times, structural features of a craft and the capsule itself, as well as unsuitability of the existing set of standard tools under these conditions and the physical restrictions imposed by the hermetically sealed space suit, interfered with successful accomplishment of certain work operations.

It was noted that theoretical proposals and tests under simulated conditions cannot replace actual experiments, with accomplishment of work operations by the operator directly in the spacecraft itself.

According to the data of some investigators, when an operator is working with a tool in a high-altitude pressure suit, fine movements of the wrists and fingers are disturbed much more than rough, strong movements. The force of compression on the wrists in the pressure suit drops considerably, especially upon discharging excess pressure.

For movement of a man along the outer surface of a spacecraft, /219 magnetic or suction footgear can be used, as well as devices with jet engines. A system operating on compressed air through a controllable nozzle ("air gun") provides about 7 kgf thrust.

Experience with this system was accompanied by uncontrollable somersaulting about the cabin, which took place as a result of noncoincidence of the thrust with the center of gravity of the body. For the purpose of stabilization of the body position under weightlessness, research on use of gyroscopes was carried out.

The stabilization system includes a small unit with gyroscopes and a computer, delivering control signals to pulse jet engines. The precision of a given position of the astronaut is guaranteed within ±2°.

Let us dwell on certain results of engineering-psychological research, obtained during the flight of A. A. Leonov in open space [4, 41, 48].

The 12-min extravehicular activity of A. A. Leonov was not accompanied, at the moment of his first separation from the craft by a sudden burst of emotional stress, as had been expected. Also, no unpleasant subjective sensations were noted at all, although the astronaut executed several multiplane rotations, and no vegetative disorders, connected with vestibular and opticokinetic stimuli, were noted at all.

The astronaut had to leave (float away from) the craft, push away from the exit lock with his arms, return to the craft, tightening the spring lock, turn his body by 90° around the center of mass and carry out a number of operations (assembly and disassembly of a movie camera and other things).

The safety spring lock permitted execution of very smooth movements. By means of a number of movements with the safety spring lock, spatial orientation of the body can even be accomplished and its angular rotation can be slowed down or accelerated.

Biomechanical analysis of the nature and features of the movements of A. A. Leonov, during training in a special ground test unit and in flight under weightless conditions, demonstrates completely satisfactory movement coordination and the possibility of executing purposeful movements and actions with the aid of the spring lock [41, 48, 71]. Using the special test unit on earth, Leonov required only a few training sessions in all, in order to execute, without error, movements in the unsupported test unit, similar to those which were planned for the flight mission. /220

During the entire time of his stay in open space, A. A. Leonov did not lose spatial orientation, holding the arbitrary orientation selected on earth and determined by the coordinates of the craft axes [41, 48].

The astronaut executed all planned work operations during the extravehicular activity. He carried out assembly-disassembly

of the movie camera, reported by radio, made an interesting hypothesis on the effect of his movements on the movement of the spacecraft and carried out a series of observations.

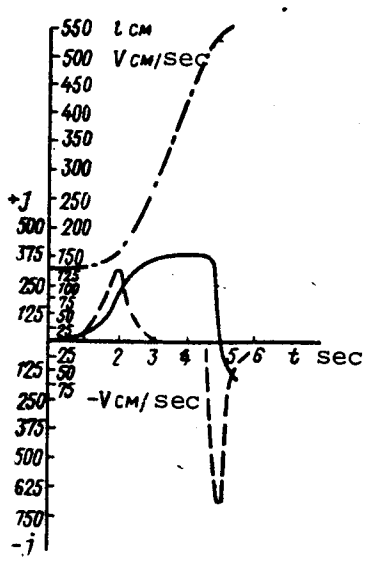

Fig. 2.6. Curves of change in distance covered (l), velocity (V) and acceleration of movement (j) of A. A. Leonov during extravehicular activity from Voskhod-2 spacecraft (from Ye. A. Ivanov, V. A. Popov, L. S. Khachatur'yants).

Curves of change in the movement parameters of Leonov during his extravehicular activity from the spacecraft mock-up under weightless conditions in an aircraft and under actual conditions of space flight are given in Figs. 2.6 and 3.6.

The flight experiment was preceded by ground training. They included both a set of physical exercises on special equipment and working out of motor activity in special test units and in weightlessness in the aircraft-laboratory, with a spaceship mock-up installed in it. During the training process in the aircraft, coordination of the movements which the astronaut had to execute in weightlessness was worked out.

Analysis of the data presented shows /221 that the characteristics of movement during extravehicular activity in space are little different from the same characteristics in training in aircraft. The time for exit into space in practice amounts to 4 sec. The same can be said for the time to approach the craft, which, in both cases, approximately equals 10 sec.

There is a somewhat greater difference in the speed of movement. On the average, this difference is 20-30% of the speed during aircraft flights, and the maximum values of the difference reach 50% [41, 48, 71].

In principle, movement of the cosmonaut can be accomplished with the aid of a number of technical attachments and devices [89].

The simplest of them are the spring lock (flexible cable) mentioned above, as well as the jet pistol (Fig. 4.6). The cable is simple and reliable, but movements by use of it are possible only for comparatively short distances. Besides, in approaching the craft on the cable, with an angular velocity relative to the craft, the centripetal force acting on the astronaut increases sharply at the moment of contact.

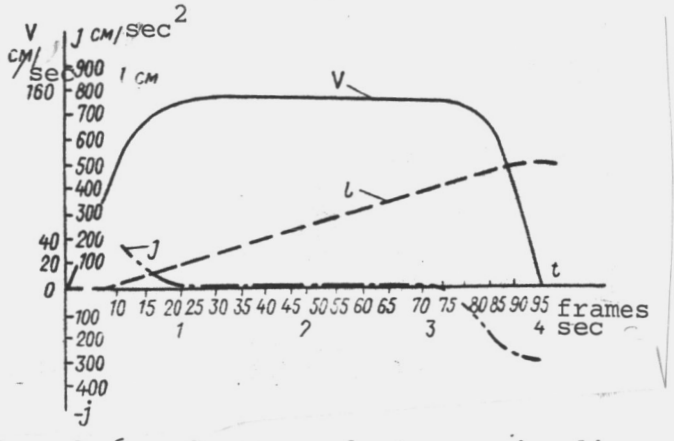

Fig. 3.6. Curves of change in distance travelled, speed and acceleration of movement of A. A. Leonov during extravehicular activity from mock-up in one of the final training flights in the aircraft-laboratory (from Ye. A. Ivanov, V. A. Popov, L. S. Khachatur'yants).

The necessity arises of independent means of movement, among which there is mainly the jet pistol referred to. This type of pistol was used, for example, during the flight of the American spacecraft Gemini-4. It has three jet nozzles, operating on compressed oxygen. One nozzle provides for movement of the cosmonaut backwards -- it is located directly on the handle and inclined somewhat upward. The other two, for movement forward, were mounted at the ends of a rod. In turning on the device, the astronaut holds it at the level of the center of gravity of his body (approximately 10 cm below the belt) and sets it in the direction in which he wishes to move.

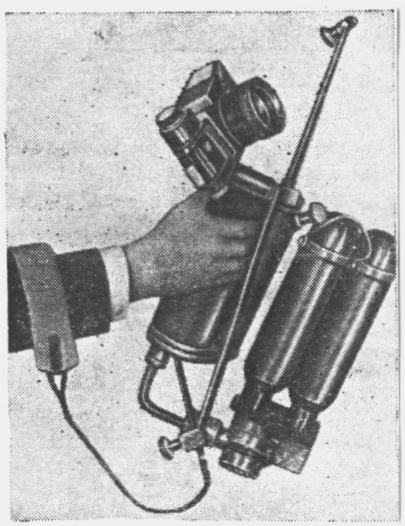

Fig. 4.6. Jet pistols for maneuvering in space (camera attached at the top).

Since the thrust vector cannot go precisely through the center of gravity, a moment of force appears, and the astronaut begins to rotate under the action of the moment of force. After a certain time, if the pistol is continually aimed at the target, the rotating moment changes its sign and the astronaut begins to rotate in the opposite direction. Countering "somersaulting" by pulling requires simpler manipulations of the pistol by the operator than in pushing. In approaching the target, manipulating the lever, the operator discharges a jet of gas ahead and brakes his movement with it. /223

The system discussed is extremely primitive. The complication in control by means of this system is that it is required that movement of the center of mass of the astronaut and its rotation relative to the connected axes be established by a single thrust vector. As the tests show,

production of a single movement does not succeed, and the principal time is spent in uncontrolled rotation relative to the center of mass. The necessity arises during movement for stabilization of the body of the astronaut, which the jet system does not provide, and the use, for example, of gyroscopic stabilization is required.

The most nearly perfect system of operator movement in open space is the backpack movement system, with automatic body position stabilization.

This system can be used by crews of mechanics in assembly or technical servicing of spacecraft in orbit or in interplanetary space.

Jet engine systems, creating rotational and forward movement of the astronaut, provide him with six degrees of freedom. American specialists consider an astronaut movement control system with variable command execution rate the most acceptable. This system increases safety in the conduct of various operations and provides more precise maneuvering at distances close to the craft.

A handle controlling rotation relative to three axes is located beside one hand of the astronaut and, for control of forward movement, beside the other one.

The magnitude of linear acceleration is 0.3-0.6 m/sec^2 and the magnitude of the angular velocities of the body of the astronaut, up to 15 degrees/sec.

In the future, when the problem of transportation of freight in orbit becomes practical, precise calculation, automation and synchronization of the operation of several propulsion units will be required. When two astronauts, having individual jet means of movement, transport some part or other, we actually will have a system with 20 degrees of freedom. It can be imagined how complicated and difficult it will be to deliver and precisely install a towed object under such conditions. /224

For carrying out work in orbit, an operator can move in a special hermtically sealed capsule, without the space suit, which hampers his movement (Fig. 5.6).

A helmet window for observation and inspection and several external, remotely controlled manipulators, "replacing" the operator's hands, as it were, are conveniently placed in the front part of the capsule. The manipulator working tools and the work place are observed v i s u a l l y as well as with the aid of the information model. During work on the surface of the craft, the capsule can be attached to the craft. The capsule can be used for moving objects and towing them [83].

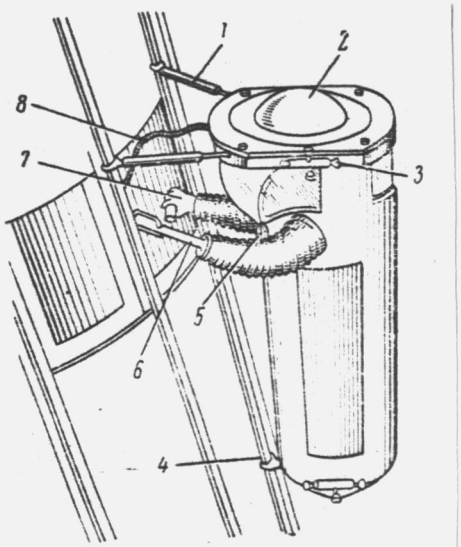

Fig. 5.6. Assembly capsule: 1. adjustable stabilizer; 2. hatch; 3. maneuvering jets; 4. external rail; 5. illuminator; 6. special detachable tool; 7. detachable glove; 8. power cable, communications and air hose.

One of the important problems of space travel is a study of the qualitative and quantitative characteristics of movement of a man during his movements in space under conditions of weightlessness. The absence of the force of gravity significantly changes coordination and the nature of movement of a man, during interaction with the bodies and objects surrounding him, forces reorganization of many accustomed motor acts and distribution of muscular efforts in a new way. A still more thoroughgoing reorganization of the constitution of movements is required when man stays in an unsupported position, when there is no possibility of the man interacting with external forces.

"Floating" in open space close to his craft does not permit execution of abrupt movements, leading to the creation of considerable linear accelerations with respect to the craft.

It is necessary to have highly developed movement coordination mechanisms, in order to execute purposeful acts and carry out active operations.

In order to select the most effective methods of turning in an unsupported position and to give appropriate recommendations for carrying them out, it is first necessary to have the quantitative characteristics of the interactions of the individual parts (components) of the human body. /225

In development of a scheme of primary and auxiliary movements, the anatomical structure of the human body (Fig. 6.6) and changes in his kinematic characteristics in various positions must be taken into account.

Certain quantitative data on moments of inertia of an operator as an object of control are presented in Table 18. They should be taken into account in creating a system for control of orientation, stabilization and movement of an astronaut in open space. In this case, it must be taken into account that the protective equipment of the astronaut will cause an increase in the indicated values of the moments of inertia [71].

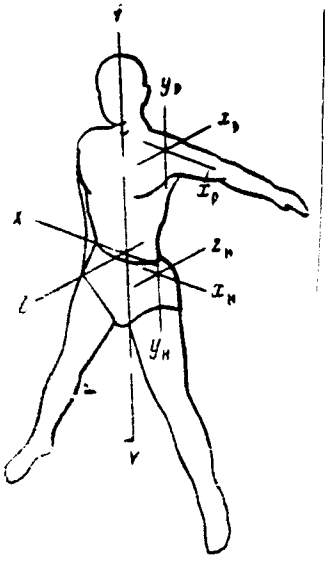

Fig. 6.6. Schematic representation of the human body and turning axes (from V. I. Stepantsov and A. V. Yeremin).

An operator, like any body in space, has six degrees of freedom -- he can move along three axes and rotate relative to three axes, rigidly connected to the body. The movement control system should provide him with movement along all three axes. Linear accelerations can be created by the same engines which are used for creation of rotational moments. /226

The body of the operator should be oriented in space, i.e., occupy a necessary position relative to the selected coordinate system. It is clear that, without control of orientation, it is impossible to move relative to the craft or the station. In these cases, the angular accelerations of the object are changed by manual control and then the angular velocities and position angles usually are proportional to the deflection angle of the control (to the control signal). Sometimes, the angular velocity of the body of the operator can be proportional to the deflection angle of the control [71]. /227

The system for control of movement, orientation and stabilization of the body of the operator should be made so that it is economical in consumption of reaction mass provides high accuracy of control and is simple for the astronaut. For approach of an operator to an object, guidance methods which are well known can be used, for example, direct guiding or parallel approach. Less thrust is required in the parallel approach than in the direct guiding method, and the consumption of reaction mass also will be less.

For accomplishment of manual control of movement, the operator should have data on his angular heading and pitch relative to the "operator-target" direction and bank relative to the target (it can be obtained either visually or by use of instruments), on distance of approach (by means of radio or optical means), on rate of approach (or departure) and angular velocity of the "operator-target" line (lateral component of velocity). The latter can be determined by the angular displacement of the target relative to the longitudinal axis of the astronaut (if there is automatic stabilization of angular velocity of the operator close to its zero value in the system).

If the astronaut is close to the craft, it is easy for him to determine his angular position and movement parameters relative to the craft and to correct the movement. If the astronaut is at some

distance from the craft, it is difficult for him to determine the parameters of his spatial movement relative to the craft and to bring out the reason for its movement in the field of vision: either as a result of rotation or due to the lateral component of velocity.

TABLE 18. MOMENTS OF INERTIA OF THE BODY AND OF ITS PARTS (FROM V. I. STEPANTSOV AND A. V. YEREMIN)

Body parts	Moments of inertia (kg/m^2) relative to axes			
	Y	X	Z	Other
Straightened body	1.2—1.4	17.0—18.0	17.0—18.0	
Head, trunk and arms	0.55—0.65	3.8—4.4	3.8—4.4	
Straight arm				x_p, y_p, z_p — 0.6
Straight leg				$x_н$, $y_н$, $z_н$ — 1.9—2.2
Legs, separated in the "spread eagle" or "step" position at an angle				
60°—70°	2.6—3.3			
120°—140°	3.9—4.4			
Straightened body less arms				x_p—24.0—28.8
Body tucked up less arms				x_p—12.0—14.4
Body less one arm				z_p—27.6—30.0
Legs in bent position	3.8—4.4	3.8—4.4	0.50—0.55	

Methods of providing feedback in the individual engine unit control system are related to quite complicated and little-studied problems. Its principles of construction depend on solution of the problem of spatial orientation of man in space. /228

Data obtained in flight and model experiments are evidence of very limited participation of the afferent system of man in analysis of the dynamics of the spatial relationships of the system referred to. Under ground conditions, the capabilities of the static-kinetic analyzer specially intended for this purpose

are restricted to weightlessness. Practically unoriented space also restricts the functional capabilities of the visual analyzer. All this determines the necessity for construction of special technical devices, which compensate for this restriction in sensory data.

A schematic diagram of a system for operator movement in open space is presented in Fig. 7.6.

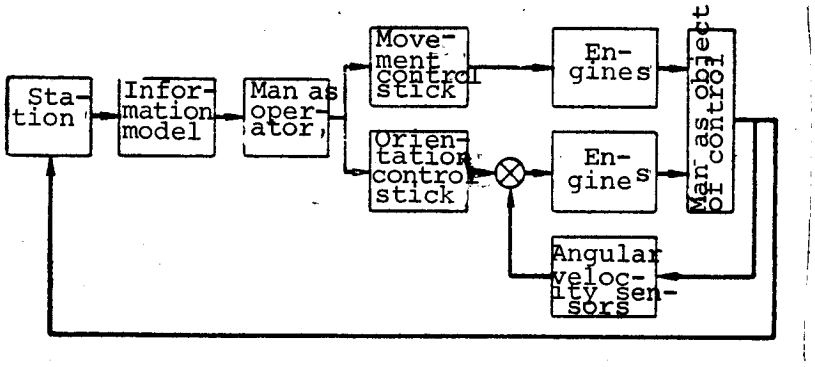

Fig. 7.6. Block diagram of individual operator movement control system in open space (from V. A. Popov, Yu. A. Rosanov and M. M. Sil'vestrov).

In this system, the operator obtains data on changes in coordinates of the orientation and movement control processes by means of observation of changes in size of the visible image of the craft and by its movement in the field of view, with the head in a fixed position relative to the body. Data obtained as a result of sighting on the craft-target is supplemented by data on the position of the starry sky, earth or moon, on the background of which the movement takes place [67]. /229

The control panel and display portion of the information model of operator movement is best placed in front of the operator's face. It is advisable to place the movement engines in the backpack, together with the independent life support system. The radio communications transmitter and receiver and the biotelemetry system transmitter can be placed there.

With expansion of the functions of an astronaut in open space, the problem of selection of efficient controls of the movement system and other systems with which the operator interacts, arises. It is clear that, because of the difficulty in control by normal levers (the presence of gloves on the hands of the operator), the introduction of button control may be required.

Operation of the man-machine system in open space has been investigated completely insufficiently. Specialists in development

of operator movement control systems will have to decide what must be the optimum values of the angular and linear velocities and accelerations of the operator, how, where and what amount of thrust pulse to "apply" to the operator for movement and stabilization of the position selected by the astronaut, what is the most suitable sequence of movements of the astronaut in the space suit and for accomplishing some specific work or other, and what are the abilities and potentialities of the operator as to orientation and determination of distance to an object under the conditions of unsupported and unoriented space.

First, the most nearly optimum methods of furnishing the operator with control signals in the system referred to must be investigated. The following should be examined: voice commands ("stop," "forward," "back," "up," "down," "bank," etc.); special levers (under the hand); possible movements of the leg, head, torso; eye movements; muscle biocurrents; movement of the lips or tongue; the use of blowing, by sharp exhalation; control by variable tone sounds and other things [29].

To guarantee successful accomplishment of various functions by man in outer space, training of future astronauts in a "weightlessness tank" in an aircraft and in a water tank, with accomplishment of tasks, which it will be necessary to accomplish in space, as well as training in special ground training units ("unsupported" test units) should be of great importance. In addition, active and passive training of the vestibular apparatus in different equipment and test units should be carried out (they were referred to in Chapter 5). /230

CHAPTER VII. MAN-MACHINE SYSTEM UNDER CONDITIONS OF PROLONGED STAY BY THE OPERATOR IN A CLOSED SPACE OF SMALL VOLUME /231

In flight in modern and prospective aircraft in the atmosphere of the earth and in space, the operator will be in a closed space of relatively small volume. This is the pressurized aircraft cabin and the working and living sections of spacecraft. The unique conditions of the closed space surrounding the operator during his work with onboard systems for various purposes frequently are unusual and, as a rule, are not encountered in the customary affairs of people on earth.

These conditions have a definite effect on the information and energetic properties of the operator, affect his overall efficiency and, in the long run, show up in the output characteristics of the man-aircraft biomechanical system.

Of course, the human body can, to a certain extent, adapt to the unusual conditions of a closed space.

Despite the fact that, in the process of adaptation, a number of unfavorable shifts appear, the body adapts in a specific way to the conditions of change in the medium of a hermetically sealed space. On the whole, a definite normalization of many functions begins: sleep, motor reactions, light sensitivity of the eyes, reduction of the number of errors in work to initial values, etc. At the same time, increased fatiguability is maintained. Thus, adaptation is relative and, since the action of unfavorable factors continues, in the final analysis, disturbance of the adaptive mechanisms takes place and, at the end of the experiment, asthenization phenomena are detected (functional insufficiency and general weakness of the body). /232

Working activities of a man under conditions of prolonged flight (especially in space) will take place under conditions which are unusual for his body and, perhaps, are so complicated that the man has to work to the limit of his physiological capabilities in individual cases.

There is practical value in the investigation of the efficiency of man in relative adynamia (immobility), in changing biological media and during prolonged isolation. As a basic test in investigation of operator efficiency, it is advisable to use those types of work activities in control systems, which are connected with receiving, processing and transmission of information, as well as generating control actions.

Characteristic features of operator work in aircraft are the absence, as a rule, of active motor activity during comparatively

long periods of time, prolonged stay in a forced low-mobility working posture in insufficiently convenient protective equipment, before the instruments and controls, and great stress of the visual analyzer.

This entire set of flight and activity factors has been given the name of relative adynamia (immobility).

Under conditions of a long flight (especially in space), muscular work of man is sharply reduced, both due to the absence of muscular efforts necessary for accomplishing physical work and due to the absence of the necessity for maintaining the vertical position of the body. As a consequence, there is a sharp reduction in the load on the cardiovascular system and the work of the heart in moving blood through the circulatory system is eased. The state of relative muscular inaction and decrease in load on the cardiovascular system is accompanied by changes in the metabolic processes. The flux of nerve impulses, continuously coming into the brain from the skeletomuscular and cardiovascular /233 apparatus and other organs become different, which, in turn, can show up in neuropsychic reactions [15, 54, 57].

Numerous works have determined that sharp limitation of motor activity causes a reduction in functional competence of the motor apparatus in man, and, as a result, deterioration of his muscular efficiency [64, 86]. Reduction in efficiency is most pronounced in those uses and actions, which are connected with manifestation of general physical endurance, strength and resistance to force and static muscular stress. Muscular efficiency frequently is reduced in movements of the arms in carrying out procedures and actions requiring maximum speed, precision, coordination of movement and skill.

The effect of prolonged immobility on the functioning of the central nervous system is manifested by disturbances of accuracy of perception of kinesthetic stimuli and accuracy of motor reactions, and in increase in the latent period of simple and complicated motor reactions. Changes in the indicators of muscle tonus are evidence of considerable fatigue.

Unfavorable physiological reactions caused by prolonged immobility affect the general health of the operator to a considerable extent, facilitating the more rapid development of fatigue, appearance of a feeling of flabbiness, weakness and reduction in occupational efficiency [91].

In a working mock-up of the cabin of the craft "Vostok," a well-trained operator must carry out daily (twice) manual control sessions in orientation of the craft as to bank, pitch and heading, using a three-coordinate control stick, for a period of 10 days [27, 30]. Evaluation of the control system and activity of the operator in it was carried out according to the combination:

time for execution of control task;

precision of task execution (mean number of errors in degrees in each of the coordinates);

the number of erroneous actions in the control process (guiding the craft to the opposite side, incomplete orientation of the craft, guidance by two coordinates, random releases of the control stick, etc.);

consumption of reaction mass (fuel) used in solution of the problems; /234

the nature of the primary neural processes and vegetative reactions with multiple recordings of the physiological functions.

During the time of this experiment, 52 studies were carried out in manual control of orientation of the craft.

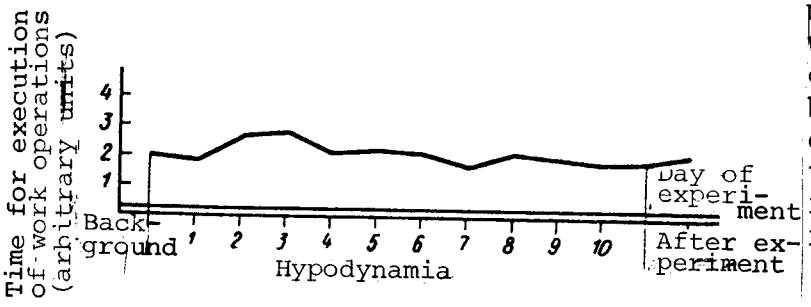

Fig. 1.7. Mean time spent in orientation of the craft in the dynamics of the experiment.

During the experiment, the nature of the working activity of the operator was not constant, but underwent certain changes. A certain tendency towards increase in the total time spent in orientation was noted (Fig. 1.7).

Thus, in comparison with the initial data, the time for orientation on the second and third days of hypodynamia increased by 25% on the average.

In proportion to further stay under conditions of hypodynamia, a regular tendency towards time indicator improvement (return to the initial value or close to it) was observed. However, precision in accomplishment of orientation tasks in each of the angular coordinates (bank, pitch, heading) decreased (Fig. 2.7). In addition, distinct erroneous control actions by the operator were recorded on the fifth, sixth and tenth days. Consumption of reaction mass, with respect to the initial background, was increased, especially during the first three days of the stay under conditions of hypodynamia.

The results of operator work activity during the daily period were not uniform. During the evening hours, a tendency towards increase in the time for orientation of the craft was observed. /235

No significant differences during the daily period were noted in accuracy of execution of control tasks or in number of erroneous actions.

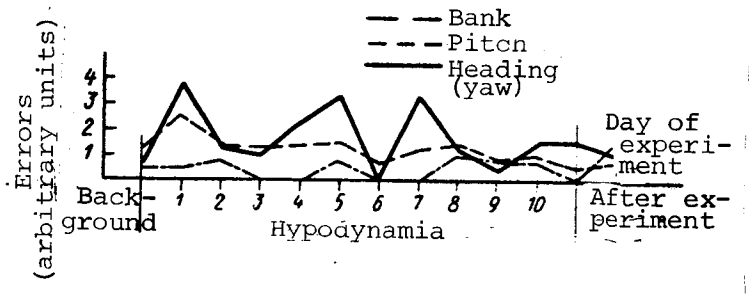

Fig. 2.7. Mean quantity of errors in angular coordinates.

Vegetative indicators (number of heart contractions and respiration), recorded during periods of work by the operators in the craft mock-up, over the extent of the entire experiment (with the exception of days 1-3), were practically unchanged. The indications did not go beyond the limits of the physiological standards. During the second half of the experiment (days 6-10), a reduction in interest in the studies being carried out was noted in the operator. Twice, he "forgot" to accomplish complete orientation of the craft (in all three coordinates), and oriented it only as to bank and pitch, but he reported that the craft was completely oriented. Precision in execution of tasks decreased. From the set of recordings of physiological functions, an increase over the initial background in bioelectric activity of the low-frequency rhythms, of 82% on the average, and a sluggish exaltation of the alpha rhythms (8-13 Hz), by 70%, were noted on the EEG [62].

On the EMG, there was a reduction in bioelectric activity of 27% on the average and a reduction in galvanic skin resistance of 30%, according to GSR data, etc. [61].

The same operator, after 1 year, in the following series of experiments (for a period of 8 days), in addition to the orientation work indicated above, had to carry out data transmission sessions (three times per day). The operator activity was considerably better than in the first series of experiments, by all indicators of activity. /236

The health of the operator was good during the 8 day period. The schedule established for the experiment was carried out clearly and accurately. Full sleep was noted during the nighttime hours. Working movements during control periods were coordinated and proportioned. Adequacy and accuracy of working movements were combined with great endurance and the ability to wait for a long time, without loss of the capacity for rapid and precise reaction to switching on of the manual orientation system. During the extent of the entire experiment, the operator maintained a heightened interest and purposeful activity during control by the

system. Negligible increase in the indicators of bioelectric activity of the low-frequency rhythms was observed in the EEG of the physiological functions recording set. In particular, delta-1 and theta rhythm (2-8 Hz) bioelectric activity increased by 22% on the average by the end of the experiment, the sluggish exaltation of the alpha rhythm during work was higher by 39% on the average at the end of the experiment, and there was a reduction in the orienting reactions of 20%, from the GSR data, etc.

The noticeable difference in the nature of operator activity in the first and second series of experiments can be explained, first, by an adaptation reaction to the novelty and unusualness of the situation, as well as by differences in the nature of the working modes of the operator themselves. In the second series, the improved quality of work of the operator was facilitated also by inclusion in the order of work of elements of diverse and uniformly saturated labor.

Under these conditions, the data transmission process was connected with increased attention and fine coordination of movements by the operator. On the basis of the experimental data obtained, it can be proposed that, under the prolonged influence of hypodynamia, one of the basic means necessary for maintaining efficiency at the initial level in control of the ship's systems is conditions providing uniform loading of the operating mode of the operator in purposeful and diverse types of work activities. This levels the unfavorable effect of the limited influx of afffer-/237 ent and proprioceptive signals, and it is a unique natural stimulus of cerebral cortex tonus during work under conditions of a monotonous medium.

Studies were carried out on the reliability of operation of the operator (i.e., the probability of troublefree work in a specified period of time) in perception and decoding of signals of "useful" data on the background of interference (noise), under conditions of many days of strict (without physical exercise) limitation of afferent signalling.

It was determined that the flow of the working process under these conditions is characterized by a pronounced instability and oscillations, which we arbitrarily call phases: adaptation (1-3 days), "stable" background reliability (3-7 days), reduced background reliability (7-9 days), emotional-affective reactions (10 days). In carrying out the study, it was noted that the sorts of the problems solved which suffered the most were the processes of differentiating of "useful" signals on the background of noise and shaping of control actions. Reliability of work, according to these parameters, dropped by 25-30% in the adaptation phase. The fact that a reduction in contrast sensitivity of the visual analyzer to red and blue light by 35 and 45%, respectively, was noted at the end of the experiment deserves attention. The

period of the day had a definite effect on the reliability of work of the operator.

It was noted that the level of reliability of work of the operator depends on the diurnal rhythm of the experiment and is determined by the phase of the working process.

The observed changes in reliability of work of the operators, apparently, can be explained by the following causes:

a) some adaptation of the neural mechanisms to the unusual conditions of the external medium in the initial period (reactions to the "novelty" of the situation);

b) development of general fatigue, as a consequence of the monotonous flow of the operating processes and prolonged limitation of the influx of afferent signals;

c) psychophysiological factors (emotional reactions, connected with the ending of the long experiment). /238

This was seen particularly graphically after carrying out analysis of the set of physiological function recordings. Thus, the appearance of diffuse slow waves, reduction in excitability and reactivity of the cells of the cerebral cortex during execution of functional tests by the operator, were noted on the EEG. An increase in the indicators of bioelectric activity of the delta-1 and theta rhythms of the low-frequency components by 22-35% was observed, and the sluggish exaltation of the alpha rhythms of 50-80% (with respect to the initial background) also was noted.

In the first days of the experiment, an increase in the muscle bioelectric activity indicators was noted, and a reduction at the end of the experiment. In a number of cases, frequent and arrhythmic oscillations were noted on the EMG.

An increase in GSR amplitude by 250-300 μV took place in the GSR recording.

As to the respiratory function (PG), no significant changes were observed. However, in carrying out functional tests, an increase in the frequency of respiration from 14 to 24 respiratory cycles per minute (after the experiment) was noted.

A tendency towards increase in the heart rate, both at rest and during work periods, was observed in the recording of cardiovascular system indicators (EKG). In carrying out functional tests, an increase in the heart rate from 74 to 152 beats/min (before experiment) and from 74 to 172 beats/min (after experiment) was noted.

The primary origin of the changes detected in the cardiovascular system under conditions of hypodynamia, in all probability, is inertness of the adaptive mechanisms of cardiovascular activity regulation during change of the body from one level of physical activity to another. Some investigators propose that, under the influence of prolonged hypodynamia, proprioceptor and cardioreceptor signalling is decreased, leading to weakening of the afferent-effector feedback of the circulatory system. This position is confirmed by the fact that a change by a man to active work leads to a gradual restoration of the disturbed relationships [8]. /239

Physical exercises under conditions of hypodynamia, as is well known, increasing body tonus, improve its physiological functioning [51], reduce the increasing requirements in hypodynamia for physical loading and arbitrary movements and indisputably have a favorable effect on operators under conditions of prolonged flight.

The problem of study of readaptation of the body of an astronaut to conditions of terrestrial gravitation after completing a prolonged space flight is of great scientific and practical importance.

The specifics of atmospheric and space flight require certain compromise between efforts to create optimum conditons of comfort for crew members and technical capabilities of putting them into practice.

The simplest solution of the problem would be to duplicate the natural environment of the existence of man on earth under space flight conditions, with the capability of using those deviations of it from average values with which man is faced on earth. However, such an approach to the formation of an artificial environment is not considered completely justified by specialists, for a number of reasons [81].

A different approach to standardization of temperature, pressure, gas and ion composition, and moisture essentially comes down to determination of the degree of "neutrality" of the artificial environment for man, which should provide him the maximum efficiency and maintenance of health during flights.

The greatest difficulties are connected with the circumstance that, in itself, a long, continuous stay by man in the cabin of a spacecraft disrupting the established stereotype of life, restricting the sphere of application of human activity and decreasing the receipt of external information, is not an indifferent "neutral" factor, and even under otherwise optimum conditions, can lead to significant functional shifts. At the same time, our capabilities of optimum standardization of the

degree of "isolation" is restricted most of all. In this connection, it is appropriate to examine the question of use of oscillations of certain parameters of the unusual artificial environment for active stimulation of action on the central nervous system and psychic activity of man. /240

The environment, changed from the terrestrial biological one, can act differently on the efficiency of an operator in accomplishing a task during flight.

The results of work activity in system control (tracking mode), during the action of changed gaseous environments on an operator, are presented in Figs. 3.7 and 4.7 [37].

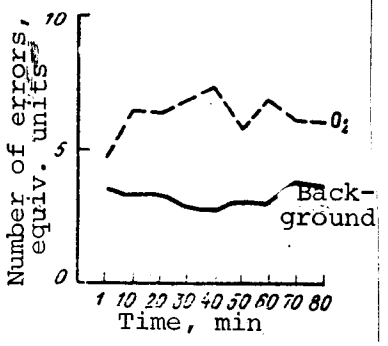

Fig. 3.7. Number of equivalent errors in tracking mode: control while breathing a gaseous mixture with 8.2% oxygen (from Ye. S. Zavyalov, S. G. Mel'nik).

Two many-day experiments were carried out. Operators having the necessary skills in work and being in a room with small volume for a period of 15-25 days, in a helium-oxygen medium, conducted data transmission sessions daily.

The results obtained indicated that no significant differences were noted in the quality of work of the operators in data transmission or in their psychophysiological stress, in normal and in helium-oxygen atmospheres, under experimental conditions [31]. /241

Temperature and moisture in the cabin environment showed a great effect on the quality of work of an operator. An increase in temperature and moisture reduces overall efficiency, leads to an increase in number of erroneous actions by the operator, decreases the reaction speed and impairs overload tolerance [90]. Sharp temperature drops, as well as high temperature gradients on the body axes of a man, have a special effect on accomplishment of work functions.[1]

In a series of experiments, carried out during long tests in chambers of restricted volume, it was established that, while, under optimum temperature conditions, the reaction speed gradually increased, as a result of training of the test subjects, during

[1] Unfortunately, there are not sufficiently thorough experimental data in the literature on the effect of sharp temperature drops and high temperature gradients on the operational activities of man, applicable to aviation and space conditions.

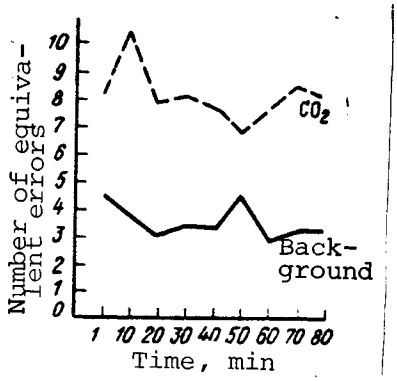

Fig. 4.7. Number of equivalent errors in tracking mode: control while breathing gaseous mixture with 9-9.2% carbon dioxide (from Ye. S. Zavyalov, S. G. Mel'nik).

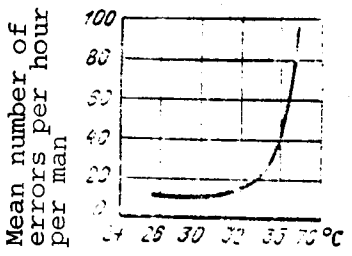

Fig. 5.7. Number of operator errors during work on a telegraph key vs. temperature of the surrounding medium.

an increase in air temperature to 40-47°, it initially dropped sharply and, only at the end of the test, somewhat exceeded the initial value.

A series of experiments was carried out to determine the efficiency of operator activity during his work on a telegraph key, as a function of change in ambient temperature. These tests show (Fig. 5.7) that the temperature significantly affects the efficiency of the operator. The number of errors during work on the key increases sharply, when the temperature of the surrounding air exceeds 31-32°C (relative humidity 60%). It also was noted that, in carrying out work in the sitting position, mental fatigue sets in before any kind of objective physiological data, for example, pulse rate or body temperature is recorded. At one and the same effective temperature, at low relative humidity (20%), the number of tracking errors is less than in moist air (80%). /242

Movement coordination at this temperature level became unsatisfactory, and concentration capability became highly restricted. The temperature mode comfort zone is presented in Fig. 6.7.

The noises which accompany AC flight and disrupt operator efficiency are of great importance for operation of the operator-AC system. During the past 10-15 years, the acoustical power of aviation noises, owing to use of high thrust engines, has increased 8-10 times. Thus, for example, the noise level created by jet engines fluctuates within the limits of 110-120 dB, and it exceeds 130 dB in some types of aircraft, reaching the pain threshold [47]. Noises in spacecraft in the active part of the flight also are extremely intense, and, in individual cases, can reach comparatively high values, on the order of 120-150 dB [17]. I. Ya. Borshchevskiy and others [5] determined that painful sensations in the ears arise at a noise level of about 120 dB. Man can tolerate a noise level, without significant functional disturbances, of the following intensities:

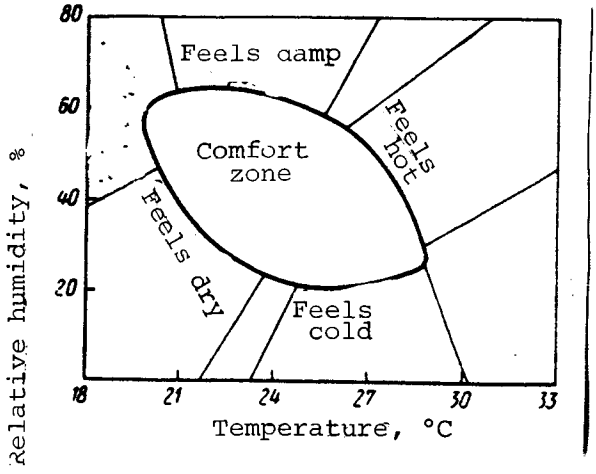

Fig. 6.7. Temperature mode comfort zone.

100 dB for a period of 8 hr
103 dB for a period of 4 hr
106 dB for a period of 2 hr
109 dB for a period of 1 hr
112 dB for a period of 30 min
115 dB for a period of 15 min
118 dB for a period of 7-8 min
121 dB for a period of 3 min
124 dB for a period of 1.5 min

Medium and low intensity noises act on a spaceship operator during all of its orbital movement: the principal sources of noises here are the operating units of the life support system, which functions continually under flight conditions and creates a constant acoustical background in the cabin. In the descent of the craft from orbit, noises in the descending craft have their origin in aerodynamic forces. The frequency of acoustical oscillations, noises, reaches 3000 Hz.

Psychoacoustically, noise in a long flight takes on the nature of a monotonous, unpleasant irritation. A pronounced cyclic nature and the uniformity of this irritation, for example, in space flight, creates conditions for the predominance of inhibiting processes in the central nervous system of the operator. /243

Functional changes also are observed in the cardiovascular system. All this leads to a reduction in operator efficiency. However, the absence of a constant acoustical background of some optimum value in the cabin is just as undesirable as the presence of noises of very high effectiveness.

It was determined by the research of Professors Ye. M. Yuganov, Yu. V. Krylov and V. S. Kuznetsov [77, 78] that, during a 30-day continuous action of high-frequency noises, with an intensity of 75 dB, on man, oscillations in the hearing threshold, with decrease in the fluctuations during the period from the fifth to the seventh and from the 24th to the 27th day of the experiment were observed. By the end of the experiment, the hearing threshold had increased by 25-30 dB. The return adaptation time increased by 3-5 times. Restoration to initial hearing sensitivity takes place in the course of 48-50 hr. A characteristic feature of these investigations was constant complaints during the course of the entire test of the irritating and fatiguing effects of the noise. After prolonged action of the stimulus, the subjects continuously perceived noise in the ears for a period of a day. The research showed that decrease in amplitude and frequency of /244

the alpha rhythm, with superimposed, diffuse slow waves, was detected in the EEG at the end of the test. Control experiments, with relative isolation and hypokinesia, permitted the conclusion to be drawn that a continuous 30-day action of noise shows pronounced unfavorable effects on the central nervous system and auditory analyzer.

It was determined as a result of the research that the continuous and periodic action of high-frequency noise, with an intensity of 75 dB, on man, differ significantly from each other, both in the nature of the effect and in the degree of change in functioning of the auditory analyzer. With periodic action of noise (up to 7 hr per day), a cumulative effect is observed only after many months and years. During its continuous action, similar symptoms are detected by the tenth day.

It has been recorded experimentally that, after the action of a 110 dB noise, containing frequencies of no more than 150 Hz, for a period of 1 sec, the efficiency of a man is left depressed during the succeeding 20-30 sec.

High frequency noises (over 2000 Hz) disrupt efficiency still more. Thus, for example, in the experiments carried out, the operator had to push the switch corresponding to the one burning lamp of five. Upon accomplishing this action, another lamp lit immediately, etc. It was revealed that the number of errors made by the operator during the action of high pitch noises was significantly greater than the number of errors made during the action of low pitch noises, only in the event that the noise level exceeded 100 dB. The noises led to an increase in the number of errors made by the operator, but did not affect the speed of executing the operation. Simultaneously, great individual differences between the operators in sensitivity to noise and in capacity for recovery of hearing after the end of the experiment were noted.

Considering that complete elimination of the effect of noise on the body of the operator practically cannot be achieved (and this is scarcely necessary), the establishment of optimum standards and relationships between the amplitude-frequency characteristics of the noise, as a physical quantity, and volume, as an expression of the psychoacoustical effect, is advisable. /245

Thus, concerning noises with a spectrum of 150-3000 Hz, some investigators (I. Ya. Borshchevskiy, V. S. Kuznetsov, E. V. Lapayev) [6] recommend the following permissible noise levels and daily exposure times: up to 100 dB, 6 hr; up to 110 dB, 1 hr; up to 115 dB, 30 min.

The correct physiological-hygienic noise standardization in AC cabins and compartments, as well as in places on earth where

there are operators controlling AC flights, reduces the harmful effect of noise on operators and shows up favorably in their efficiencies.

A. V. Gromov and V. S. Kuznetsov [19] point out several solutions of the problem of protection of operators from noise and the establishment of acoustical comfort in cabins. Three methods which are more or less clear include the following: decrease in noise at its source, absorption or reflection of acoustical energy before it penetrates the crew compartment and providing crew members with personal protective equipment [19].

There is little hope of decreasing rocket noise at its source. Concerning reduction of noise in aviation, individual and collective means of protection are used here. Among the individual means of protection are antinoise devices of various constructions (plugs, semiplugs, silencers, noise protection helmets), protecting the ears from direct action of sound waves. Collective means of noise reduction are such methods as construction of engines with silencers, the use of attachments on the intake and exhaust nozzles, the use of stationary airport exhaust mufflers, the construction of sound protection booths, bunkers and stalls, and the introduction of methods of remote monitoring and control of units giving off noise. It is possible that the most acceptable solution will be absorption and reflection of noise between the source and the crew. Since the principal source of acoustical energy will be outside the crew compartment, sound impervious insulation around and within the compartment will be the most effective means of protection. Protection of the crew by individual means, for example, silencers, will have little effect under these conditions. True, silencers permit reduction in intensity of jet aircraft noise acting on the ears from 130 dB outside the helmet to 100 dB at the entrance to the auditory duct. In this case, the spectral nature of the noise is changed and becomes of a lower frequency, and this is a favorable fact, since the high frequencies have great traumatizing action [19]. However, the sound vibrations generated in air, at sufficient intensity, can cause vibration of the skull, which can be transmitted to the cochlea. The threshold of bone acoustical energy conductivity is quite high, in comparison with the sound conductivity of air. Therefore, even if the silencers attenuate the sound by 40-60 dB, the possibility of trauma is not excluded since the noise reaches power on the order of 140 dB and more [19]. /246

The isolation of an astronaut in a spaceship becomes especially important for operator activity during distant interplanetary flights.

Being in "space isolation," man, besides the effect of purely physiological factors, depending on the unusual environment, is subject to effects of a psychological nature. They appear in the

forced "breakaway," from the outside world, disruption of accustomed circumstances and, finally, in the uniform conditions of existence, when incoming information is considerably restricted [18].

Among the psychological and social factors are: boredome and restriction, disorientation, mental fatigue, motivation, neuroses, personal conflicts, fear, psychoses, insomnia and others. Study of these problems, in connection with the feeling of the "unknown" in space flight (especially weightlessness, radiation and stress) definitely presents a new situation.

Psychological factors cannot be precisely and clearly classified like physiological ones. These factors and their interrelationships are more complicated than physiological ones, and quantitative data on them are quite insignificant. This does not permit establishment of acceptable limits for them. Moreover, a practical simulation of the majority of them, like for example, fear, practically is not encountered. Therefore, there is little likelihood that the effect of such factors will be completely foreseen before a flight, for example, to other planets. Under these conditions, a practical solution only leads to a qualitative /247 selection and training of astronauts and to provision of appropriate physiological and psychological situations, which reduce either the presence of unknowns or the action of undesirable factors to a minimum.

In analyzing isolation, we have to do with a many-sided problem: one of its aspects is solitude, another is the feeling of distance and a third is "isolation" from society. Intercourse with one another is necessary for the majority of people. Isolation sharply reduces perception and feeling. If the number and diversity of sensory stimuli is too small, disruption of perception is possible. Proprioceptive sensitivity of the muscles and joints is especially important.

The work of Soviet scientists and experiences of comparatively long flights in spacecraft shows that, with appropriate selection and training of operators, with optimum loading of them with purposeful activity, the problems of relative isolation can be solved (at least for flights around earth). Isolation and the possible disturbances of efficiency connected with it probably are not factors which significantly reduce effectiveness of operation of the operator-AC system [18, 54].

The so-called space stress, arising from the close proximity to other people, is of separate importance.

In experiments, simulating the conditions of a prolonged stay of people in a closed space of sharply restricted volume,

it was determined that the "congestion factor" is of significant importance. Closeness leads, to a certain extent, to reduction in efficiency and increase in irritability of the participants in the experiment. It is evident that there is a certain three-dimensional area which is necessary for each man in prolonged proximity to other people. The experiments fully confirmed the necessity for taking account of psychological compatability of spacecraft crews.

Among the adverse factors, the cost of the monotony of conditions of existence, arising as a consequence of standardization of the work, rest and eating conditions, is a certain aloofness [35, 55]. The fact of the matter is that, if the restriction of data in itself has an adverse effect, standardization of living conditions and a strict schedule, as is well-known, have their positive side, especially if it is taken into account that all the test subjects were healthy young people. As a result, standardization of living conditions among the test subjects generated a new, forced stereotype in the flow of the majority of physiological functions. /248

In interplanetary flight, geophysical factors, connected with the daily rotation of the earth (the interchange of day and night, increase in temperature and increase in cosmic radiation in the daytime and other things), begin to act on a man. Therefore, the problem of study of the biological rhythms has great scientific and practical importance.

Specialists in industrial hygiene have revealed a definite effect of the arrangement of the day on the physiological processes of work and rest in man. The results of their research can be taken advantage of to a certain extent as a basis for the rhythm of activities of the crew of an interplanetary craft.

It can be clearly imagined that the operator on a long flight will be in a state of readiness to act (waiting mode) during a considerable part of the time.

This state requires intense attention and sharpened hearing and vision. In the process of research, it was determined that, even under terrestrial conditions, being in such an observation mode for 5-6 hr, the attention of the operator becomes dulled and the reliability of his work drops sharply. Therefore, the specialists propose restricting the optimum time for efficient work in the craft to not more than 4 hr.

The various diurnal rhythms were studied in an anechoic chamber. The "inverted rhythm," when the subjects slept in the daytime and worked at night, and fractional, two-phase and three-phase rhythms, when, in one case, in the period of 24 hr, they carried out operator work two times, actively rested and slept

and in the other, did this three times. It turned out that the more the activity conditions diverged from the customary, the more heavily it bore on man [57].

With renewal of the normal mode of daily activity, the initial level of efficiency is restored in the test subjects in 2-5 /249
days, and they begin to sleep during the hours removed from the routine.

Fatigue has a great effect on operator efficiency during a long flight.

The physiological nature of fatigue, arising under the influence of various types of activity, including flight, as is well-known, is connected with the onset of the so-called protective inhibition in the cerebral cortex, which is characterized by a reduction in the functional capabilities of the nerve cells. This is immediately reflected in the general condition of the man. His attention becomes dulled, memory and alertness deteriorate and speed, accuracy and movement coordination are lost. All this shows up in the tempo, productivity and accuracy of the work and leads to all kinds of mistakes and errors in counting.

Efficiency and, consequently, speed of development of fatigue are not the same in different people and depend on the degree of training for one type of activity or another (qualification), functional state, emotional disposition of the man and other reasons. Adaptation (accommodation) physiological mechanisms of the body play the leading part in attainment and improvement of overall efficiency. Development and strengthening of habits and automatism of work processes and, in flight work, systematic and rhythmic flight training and efficient organization of work, rest and eating have important roles [65].

Physical culture and sports have exceptional importance for increasing overall efficiency of the human body, as well as its resistance to fatigue.

The results of experiments, obtained with subjects in the anechoic chamber, under conditions of long isolation, while carrying out three-time daily information transmission sessions, are examined below.

It was revealed that habits formed were subject to change under conditions of isolation. During the first days of isolation, a noticeable increase in the time for transmission of a text took place in all subjects, despite the fact that the intervals between the last training and the first tests under conditions of isolation were not more than a day. The time for transmission of /250
information in the first tests under conditions of isolation increased by 1 min on the average in all subjects (mean time for

transmission of text before isolation was 4 min). Subsequently, a reduction in the time for transmission of information to the initial value or close to it was observed. The rate of recovery of the time indicators under conditions of isolation were different in all subjects. At the end of the working day, in nearly all tests, the number of errors increased for all subjects.

During work time in the first days of isolation, a shift in vegetative reactions, in the direction of increase in respiration and pulse rate, and the appearance of a pronounced galvanic skin response were recorded in all subjcts.

The so-called "rest" and "aftereffect" biological currents were noted in the EMG in the first days.

An increase in the transmission time and number of errors occurring in all subjects during the first days of isolation, as well as the change in the vegetative components (GSR and the appearance of the "rest" and "aftereffect" biological currents in the EMG) are evidence of an increase in emotional reactions, caused by the "novelty" of the unusual situation.

Adaptation to the conditions and recovery of initial characteristics of existing skills in data transmission by the subjects, in proportion to the stay under conditions of isolation, began. Recovery of time indices of work, recovery of the vegetative component to the initial value, reduction in GSR amplitude and the absence of "rest" and "aftereffect" biological currents in the EMG are evidence of this.

The average number of errors of each subject during work under conditions of isolation was higher than the average number of errors of a trained subject working under normal conditions in all cases. The increase in the average number of errors under conditions of isolation (in comparison with initial data), apparently is the result of depression of the differentiating processes, taking place under conditions of restricted influx of sensory data. The appearance of a large number of errors in data transmission in the evening work hours, under conditions of isolation, should be considered as the result of increasing fatigue during the course of the working day [53].

In the opinions of many investigators, it is advisable to use a specially developed set of physical exercises, as natural stimulators, increasing the working tonus of the cerebral cortex and nerve centers, under conditions of considerable reduction in the influx of afferent stimuli to them [51]. /251

There are indications in the literature that specialists are carrying out experiments in control of fatigue, using physiological actions of pharmacological agents, which show a favorable effect on the stability of the body.

It should be assumed that, during long interplanetary flights, the professional skills of the operators might decay without appropriate reinforcement. In connection with this, there is the problem of development and use of specialized onboard trainers for maintenance of the necessary skills of the astronauts in carrying out vitally important operations during long space flights. Such trainers are all the more necessary, although it is still not clear how the psychophysiological control capabilities of an astronaut change under the influence of the extreme conditions of space flight, in comparison with those capabilities which the astronaut has on earth, carrying out the preliminary training program. Among such trainers might be, for example, an earth or planet landing trainer, a trainer for mooring to a space station and others. The onboard trainer should not be bulky, and it should be provided in the form of elements of use of onboard display, signal indication, manual control and computer systems, existing in the spacecraft.

A test unit for investigation of the dynamic characteristics of the operator and his psychophysiological control capabilities, under different flight conditions and environments, as a rule, is a unit of models of dynamic links (amplifying, inertial, integral, relay, combined), display devices by which control is exercised, controls, programming devices, recorders and devices for objective determination of the quality of execution of the mission. Displays should provide indications of the control process, with a frequency on the order of 2-3 Hz. Production of trouble signals should be provided in the model unit, in the form of single, random functions and sinusoids. The programming device should provide for assignment of various characteristics of the dynamic links (time constant, damping coefficient, frequency of the disturbing signal and others). /252

Investigation of the dynamic characteristics of the operator in flight in a spacecraft,by one such portable test unit has been described by Professors P. K. Isakov, V. A. Popov and L. S. Khachatur'yants [4, 45]. Multistep, random and sinusoidal signals, with nonmultiple frequency responses, are used as input signals.

It is possible for the operator to exercise control by direct and delayed feedback to the system. The results obtained show that, on a space flight, in comparison with data taken in the craft mock-up and in trainers, the root mean error of the operator increases with increase in frequency of the observed signal (up to 25%), and more noticeably at high frequencies (Fig. 7.7).

During a long flight, under conditions in which the operator is in a closed space of limited volume, there is a set of tasks which require continuous attention of the operator, accompanied

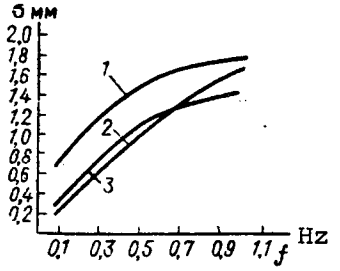

Fig. 7.7. Characteristics of the results of work of astronaut P. I. Belyayev with model control system: 1. flight; 2. training; 3. launch day (from P. K. Isakov, V. A. Popov, L. S. Khachatur'yants).

by the production of comparatively complicated, but routine, frequently repetitive, monotonous operations. This is the navigation calculations of the crew. Engineering psychology has determined that this work always is fatiguing for the operator, that the operator frequently makes mistakes in carrying it out, and that, for greater reliability of results, he should repeat the calculations which, in turn,leads to a reduction in their accuracy. The volume and the necessary speed of calculations exceed the capabilities of the operator. There is one escape here. The operator must use navigation computer technology for navigation calculations and, thereby, free /253 himself for creative activity, which is necessary for him, as the navigator, in carrying out very intensive work.

Various automatic devices and multiple systems, with central onboard navigation parameter computers, come to his assistance.

The fact that, even during work with autonomous navigation means, the functional connections between them must be taken into consideration, speaks of the necessity for complexing. Thus, for example, the heading cannot be measured by means of an astronomical compass, without knowing the coordinates of the aircraft. Directional gyros and course systems require account be taken of the geographic latitude of the point. For precise determination of the horizontal distance with the aid of onboard radar, the flight altitude, which is measured by the altimeter,must be known, etc.

Still another important reason for use of complexing is the necessity for solving navigation problems under conditions of unsteady flight, i.e., in reaching a given line and descending. With increase in speed and altitude, solution of these problems by previous methods becomes impossible: averaging the values gives an unacceptably low accuracy of calculation.

The navigation situation can be presented with the aid of:

needle indicators or indicators with counters;

display-plotting boards with moving maps or movable indexes;

screens with color slides of map sections projected on them.

Needle indicators or indicators with counters usually give the operator (navigator) the values of two coordinates of the AC location in the geographic, provisional-geodetic or flight systems of coordinates. The operator should have the appropriate navigation chart, on which he determines the AC location, using the data of the indicators.

The display-plotting board is a device showing the location of the aircraft on the terrain map (Fig. 8.7), in which the map area may be restricted to the region lying on the flight route [21, 25]. Cartographic material is used in the form of roll or sheet maps, which are completely or partially visible on the face of the plotting board. The aircraft location is marked on the map with an index, sighting crosses or light blips. Movement of the map (or indexes) is accomplished by signals from the automatic course calculator (course plotter). /254

The principle of operation of the third type of display (Fig. 9.7) is the optical projection of cartographic data, in the form of microphotographs on a transparent film or microfilms. Movement of the image is achieved by means of movement of the micromap or microfilms relative to the objective, by means of the tracking system or movement of elements of the optical system (projection objective), by signals from the automatic course calculator.

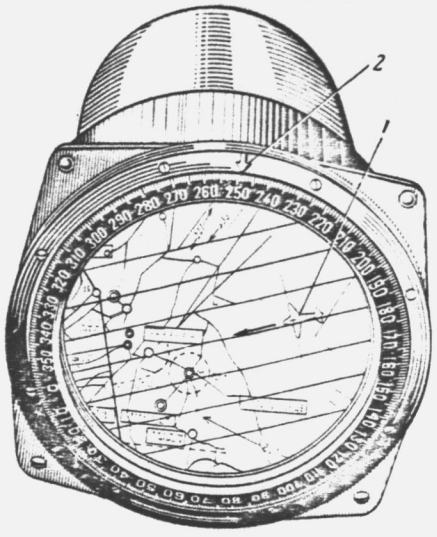

Fig. 8.7. Location and heading indicator display: 1. aircraft location; 2. aircraft heading.

To take in a larger or smaller section of the terrain, various magnifications can be used. An image of the aircraft and a grid of parallel lines, automatically orientable in a selected direction, are superimposed on the map projection.

The use of automatic navigation systems with participation of a navigator in their operation, significantly increases the reliability, accuracy and operational importance of navigation measurements in flight.

Development of a cabin interior and onboard compartments and the entire objective-spatial environment of the astronauts in the cabin, as well as development of other measures (musical accompaniment on the flight, "color climate" in the cabin and like), are of great importance for guaranteeing high efficiency of the operation-astronauts during a long flight. Engineering

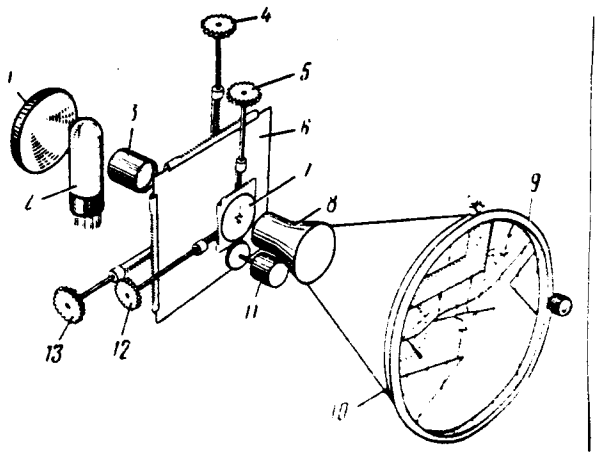

Fig. 9.7. Aircraft map location indicator (autonavigator): 1. reflector; 2. lamp; 3. condenser; 4. and 13. x and y coordinate map movement mechanisms; 5. and 12. grid movement mechanism; 6. map color slide; 7. grid; 8. objective; 9. rotating ring; 10. screen; 11. course drive mechanism.

psychology in aviation and astronautics already is closely involved with technical esthetics in solution of these problems.

A series of closely interconnected factors can have a great effect on the choice of color and color systems. A diagram of their correlations is presented in Fig 10.7. The artist-designer participating in building an AC cabin can obtain much from this diagram and use all these connections of external conditions in color decisions on components of the cabin [29].

It must be noted that, in the opinions of foreign specialists, a most widespread fallacy exists in the practice: the use of clashing colors, as supposedly giving the most visible contrast, without /257 taking account of the fact that they are mutually cancelled by their simultaneous presentation. To avoid such an error, a list of optimum color combination is proposed (Table 19).

TABLE 19. PREFERABLE COMBINATION OF SIGNAL COLOR AND BACKGROUND COLOR

Signal color	Background color
Yellow	Black
White	Blue
Black	Orange
Black	Yellow
White	Red
Orange	Black
Black	White
Red	Yellow
Green	White
Orange	White
Red	Green

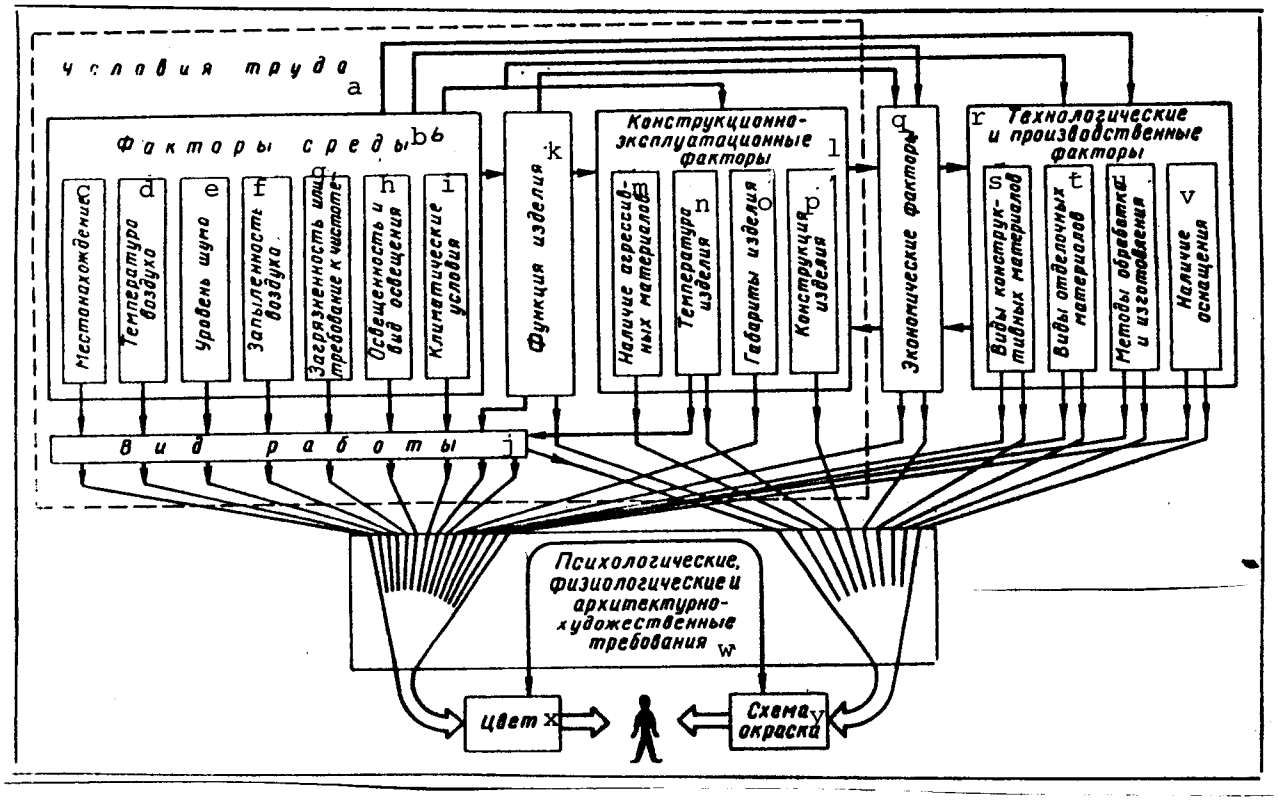

Fig. 10.7. Diagram of correlation of factors affecting color and color systems of an object (from S. A. Solomonov and N. S. Tuberozov).

Key: a. Working conditions; b. Environmental factors; c. Location; d. Air temperature; e. Noise level; f. Air dustiness; g. Soiling or requirements for cleanliness; h. Illumination and type of lighting; i. Climatic conditions; j. Type of work; k. Function of object; l. Structural-operational factors; m. Presence of reactive materials; n. Temperature of item; o. Dimensions of item; p. Structure of item; q. Economic factors; r. Technological and production factors; s. Types of structural materials; t. Types of finishing materials; u. Methods of processing and manufacture; v. Presence of equipment; w. Psychological, physiological and architectural-artistic requirements; v. Color; w. Color scheme

If the general background of the AC cabin has a dark tone, the most important monitoring instruments and controls should contrast well with the background, either in color or luminosity. In addition to that, a series of experiments show that light tones are the best background.

In concluding this chapter, the necessity should be pointed out for providing operators on a long flight with reliable and operationally important checking of their psychophysiological condition, making possible some prognosis of this condition over the required period of time. This is especially important for space flights, taking place under complicated and still little-studied conditions.

CHAPTER VIII. OPERATOR-AIRCRAFT SYSTEM ON THE EARTH /258

Problems connected with solution of tasks of training operators to carry out various control tasks in an AC occupy one of the main positions in engineering psychology in aviation and astronautics.

It is known that the psychophysiological capabilities of a man (sensory, computing and motor) are not constant, with given values once for all. They depend on many factors and change in the process of learning, in proportion to acquisition of practical experience.

Thus, an experienced pilot determines the rotation rate of the turbine shaft by sound, with an accuracy of 1-2%, and a less experienced one, with an accuracy of 8-10%. The resolving power of the eyes in binocular vision of a trained stereoscopist-interpreter is a few angular seconds, in place of 1 min for the "average" man. Experienced dyers distinguish up to 100 shades of black.

The problem of trainers and training of operators in the formation of professional skills in them is very important. A trainer is a model of an actual object, a training aid, permitting the formation of skills necessary under real working conditions (in distinction from visual aids, which only facilitate forming necessary knowledge). A trainer should be used for repeated, systematic exercises, with account taken of all rules distinguishing exercise from simple repetition. Repetition in itself does not improve and does not develop skills. Without an effort by the trainee to increase the quality of activity carried out, without his constant desire to work better, there generally cannot be exercises. /259

In examination of the basic psychological requirements, which are placed on any type of trainer, one should proceed from the fact that skills formed in a trainer should, not externally, but by their psychological structure, correspond to actual work habits [65]. Two types of trainers, one, in which a complete, complicated work skill can be practiced, and another, in which a partial work skill can be practiced cannot be set against one another. If a trainer highly automates some partial skill, which is necessary to the work, it is useful and it assists in further development of more complicated skills, which must be fixed in more complicated trainers. True, these complicated trainers cannot completely simulate all conditions of actual work activity (for example, danger, cruciality and emotional background in general and other things, for AC operators). It means that such a trainer must have to do with more or less articulated parts of the complete work activity. The whole question is to see that this articulation is done consciously and with justification.

Aviation Trainers

A piloted aircraft is an extremely complicated machine, the control circuit of which necessarily is closed through a man. Flight effectiveness, precision and safety of some aircraft or other, with its control system, having a certain degree of automation and equipped with a set of flight-navigation instruments, of course, depends only on the flight skill of the pilot.

The skill of a pilot is determined by his competence, speed and precision of reaction and action on the controls of the aircraft, as functions of the nature and degree of deviation of the aircraft from a planned program, which is determined by the readings of the aviation instruments, i.e., it depends on his transfer function, if the pilot is considered as a component "element" of the control circuit.

For repetitive actions, this transfer function can be improved to a considerable extent, due to training, i.e., training under ground conditions in trainers. /260

It has been determined that pilots who have gone through training in ground trainers read the instruments in flight more quickly and accurately, and that they are distinguished by more perfect coordination of movements, and that their voice and motor reaction latent period during interrogations on flight parameters is shorter. All these properties are progressively improved in the course of training. During flights in aircraft, pilots use the training skills and training has a favorable effect on the level of efficiency. And, in this respect, experienced methodologists are right, when they defend the idea of wide use of diverse flight trainers in flight schools and units.

However, of course, it is scarcely possible to carry out a complete course of pilot training in control of an aircraft in actual flight in ground trainers, since a trainer is, as a rule, only an approximate, incomplete model of an aircraft, and "flight" in them is not identical to flight in an actual aircraft, if only because they have a different emotional color. Therefore, the optimum solution of the problem of training flight personnel in aircraft control lies in a reasonable combination of ground training and flight training in training aircraft. Instrument flight training is carried out regularly and without fail after breaks in flight work, even if they are not especially prolonged.

Control of a modern aircraft requires possession of a whole set of complex skills, which include all pilot activity and his capacity for distributing and switching attention and coordinating his movements.

It is not difficult to ascertain that this actually is so by these examples. In order to bank the aircraft, deflect the control stick sufficiently to one side or the other. However, a turn or bank cannot be executed by only this simple movement. A proper turn is produced only if the assigned bank and flight speed (forward and angular) are strictly maintained, and the flight altitude or planned vertical speed of climb or descent is kept unchanged. /261

It requires specific skills to take off confidently and competently. For the calculated number of seconds the aircraft run lasts, the pilot must strictly hold the direction, and raise the front (or tail) wheel at the proper time; after the machine takes off, he changes it to climb, with a smooth departure from the ground and performs many other operations.

The pilot requires more complex skills for flight in formation, at night and under complicated meteorological conditions. And when a pilot begins a combat mission under such conditions, he has to manage the aircraft perfectly.

Experience shows that flight skills can be acquired only by unremitting and purposeful training.

The successes achieved during the last decade in the field of computer technology now permit very wide use of ground trainers for flight instruction and training of flight personnel, in which nearly all conditions encountered in flight can be created (simulated) [21, 23].

It can confidently be said now that an hour of "flight" in a ground trainer is equivalent to an hour of flight in an aircraft, in effectiveness of instruction and training. And it should be considered in this case that "flight" on the ground in a trainer, of course, is safe, does not depend on meteorological conditions, owing to which much valuable time is lost in pilot training and, indisputably, is more economic in expenditure of financial means (1/10-1/100) and consumption of material resources.

The time for training operators for professional activity, using computers in one of the types of trainers, according to foreign data, is decreased by two-thirds. If it is considered that still, before World War II, the duration of fighter pilot training amounted to 1/4 of his service and cost $50,000, according to the data of these same sources, it can be imagined what economy of means and time wide use of trainers gives.

Trainers permit successful retraining of flight personnel, upon replacement of materiel by new materiel, and accomplishment of checkout and evaluation of pilot readiness before their dispatch on a flight in aircraft of other types. This checkout can be more thoroughgoing than can be provided in a training aircraft. /262

In particular, the necessary reactions (actions) of the pilot can be worked out in simulation of emergency situations, which is impossible or dangerous to create in an aircraft in actual flight. Change in visibility conditions during a "flight" along a route and in a landing approach also can be simulated in a trainer, according to the program which is the most appropriate, from the point of view of the pilot-instructor.

Moreover, trainers permit their use for improvement ("matching") of desired aircraft characteristics, components of its control system and flight-navigation instruments, in the process of design of a new aircraft and its equipment, before the first flight of a test aircraft. Possible errors in design, still in the process of design of the aircraft, can be revealed and eliminated in this case. All aircraft control actions of the crew at any flight stage also can be followed very precisely, with the aid of trainers, in which appropriate control equipment is installed, and, in this manner, urgently needed information on the actions of a man, under conditions of standard placement of controls and instruments, can be obtained.

Aviation trainers, from the point of view of the functions they fulfill, can be divided into four large groups.

The first group should include the so-called flight trainers, in which a pilot develops skills in the techniques of flying and navigation of an aircraft by instruments, i.e., in "blind" flight.

The most complicated of these trainers can also simulate takeoff and landing under conditions of visual orientation.

The second group of trainers is the so-called specialized trainers, in which instruction and training of a pilot and other crew members is conducted, in use of navigation, communications and armament systems, various instruments and other special and radio equipment in flight. /263

In the third group are multiple trainers, which are a synthesis of trainers of the first and second groups. These trainers are used for "playback" or simulation of an entire flight, with the execution of various tasks during the flight, for the purpose of working out the interactions of all crew members, for example, for working out the techniques and tactics of interception and conduct of fire, using radar and optical sights, carrying out photography, flight refueling of the aircraft and other things.

The fourth group of trainers includes trainers which simulate conditions of the external environment. These trainers are intended for testing a pilot, for example, in the effects and tolerability of G-forces arising during flight, low pressures and rapid pressure drops, low and high temperatures and the actions

of other changing factors of the external environment accompanying an actual flight. Trainers for instruction and training in catapulting and touchdown also can be included here. We will not dwell on the features of these trainers.

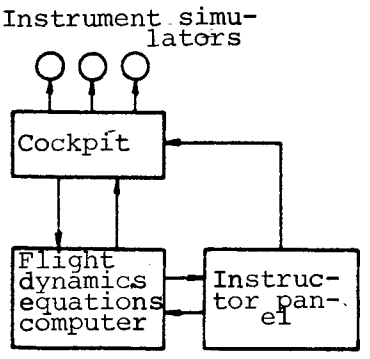

Fig. 1.8. Flight trainer block diagram.

A block diagram of a flight trainer and the basic simulation circuits of a multiple aviation trainer are presented in Figs. 1.8 and 2.8.

The flight dynamics simulator is a regular electronic integrator, in which the aircraft lateral and longitudinal movement equations are set up. The flight dynamics computer continuously solves (integrates) the aircraft movement equations.

As a result of integration of the aircraft movement equations, voltages, proportional to the angular velocities and angular deflections of the aircraft relative to the axes of the coordinate system, can be produced at the electronic model output. Voltages characterizing the pitch and bank angles (after transformation into a stationary, ground coordinate system) are used for operation of the bank-and-pitch indicator simulator. Voltages, proportional to the yaw angle and its rate of change are used for operation of the turn indicator simulator and course indicator simulator of the system (after transformation of the coordinate system). A voltage, proportional to the slip angle, obtained by integration of the aircraft lateral movement equation, is used for operation of the slip indicator simulator. In this manner, each movement of the controls by the operator will be recorded by the instrument simulators. /265

By means of appropriate selection of the parameters of the transition devices in the trainer, identity of the readings of the instrument simulators and the readings of actual instruments is achieved.

The use of continuously operating computers for simulation of the flight dynamics is more to be preferred, since such devices operate in real time, i.e., the calculation processes are carried out at the same speed as the analogous processes in the actual aircraft which they are simulating.

An electromechanical computer can be used for simulation of flight dynamics. In this case, signals from the trainer controls are transmitted through electronic amplifiers for actuation of a large number of interrelated electrical servomotors, which make up the simulating computer. These electrical mechanisms are

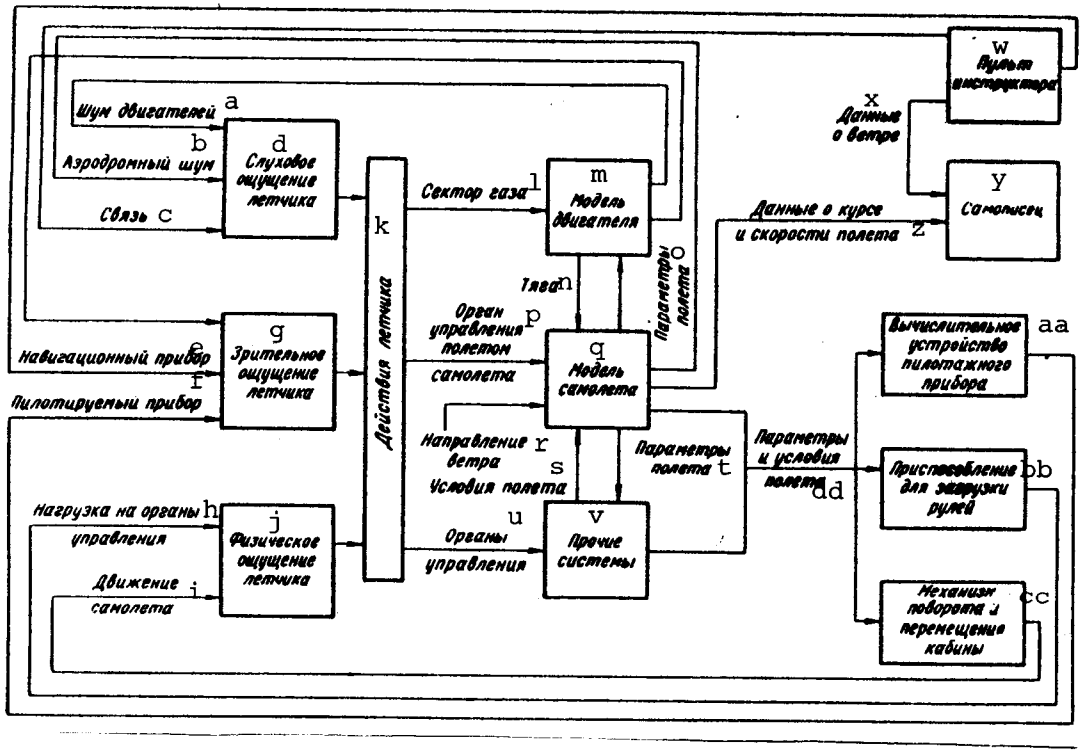

Fig. 2.8. Basic simulation circuits of a multiple aviation trainer.

Key: a. Engine noise; b. Airport noise; c. Communications; d. Pilot auditory perceptions; e. Navigation instrument; f. Flight instrument; g. Pilot visual perception; h. Load on controls; i. Aircraft movement; j. Pilot physical perception; k. Pilot actions; l. Throttle; m. Engine model; n. Thrust; o. Flight parameters; p. Aircraft flight control; q. Aircraft model; r. Wind direction; s. Flight conditions; t. Flight parameters; u. Controls; v. Other systems; w. Instructor panel; x. Wind data; y. Recorder; z. Flight heading and speed data; aa. Flight instrument computer; bb. Control surface loading adapter; cc. Cabin turning and movement mechanism; dd. Flight parameters and conditions.

reversible integrators, driven by electric motors or position tracking systems connected with block of potentiometers, the windings of which are profiled for reproduction of various functions, in the form of voltages. These voltages are combined to provide the interactions of the computer servo mechanisms and, in this manner, solution of the corresponding equations is carried out.

For simulating the operation of aircraft engines in trainers, either an electronic model or electromechanical integrators are used. After collection and integration of the engine equations, the voltages produced at the output are proportional to the rotation rate of the turbo compressor shaft, exhaust gas temperature, thrust and other parameters. Voltages proportional to the engine rotation rate and gas temperatures enter the visual monitoring display simulator inputs. A voltage, proportional to the engine thrust, is fed into the aircraft longitudinal motion equation simulator circuit. Signals proportional to the deflection angles of the aircraft control surfaces (elevator and bank control choke valve levers) are directed to the aircraft and aircraft engine dynamics simulation circuits. /266

The hydraulic and fuel systems can be simulated by means of an electrical circuit, the current strength in which is set in proportion to the flow of hydraulic fluid or fuel, and regular relays and switches "play" the role of cocks and dampers in the main lines.

The autopilot in trainers usually is represented by an amplifier and steering machines. The actual autopilot sensing elements are absent. Signal input for shaping the necessary concontrol patterns from the corresponding parameters is provided by the flight dynamics simulator. A more successful solution of the problem is the use of actual autopilots, together with the sensing elements, in trainers. Then, several standard shunts are required, to the inputs of which the voltages of the corresponding simulators are supplied. The output of such a shunt can be a physical value, measured by the sensing element, an angle or an angular velocity.

The servo mechanisms for simulation of loads on the controls usually are electrohydraulic systems, which act on signal from the flight dynamics simulator. A change in rate of climb or true airspeed forces the hydraulic servo mechanism to increase or decrease the load on the controls, using a mechanical spring.

Both random noises and sounds having specific frequency components or series of components can be reproduced in the trainer. Among the latter sounds are the turbine whistle (changing pitch and intensity in accordance with displacement of the throttle lever), the noise of the hydraulics and compressors, forcing air into the pressurized cabin, and the rustling of the tire treads on the earth during the takeoff and landing runs. /267

Among the random noises are noise of the airstream passing around the aircraft, exhaust gas noises, the knock of raindrops on the glass, the rustling of the wheel brakes, the sounds of shots and other things. The noises and sounds can be reproduced either by means of sound recordings, made in an aircraft in flight, or artificially, using electronic circuits. Random noises usually are reproduced with the aid of a "white noise" generator.

To provide the necessary frequency spectrum, characteristic of a specific sound, appropriate filtering circuits are used. For reproduction of sounds having a discrete frequency spectrum, a controllable frequency sound generator is used.

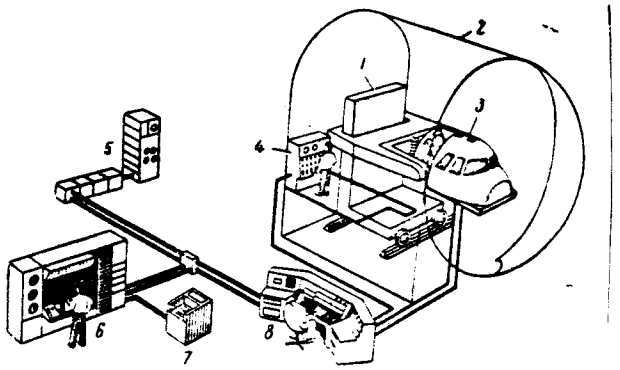

Fig. 3.8. Composition of dynamic simulator equipment: 1. mobile 5-stage platform; 2. canopy; 3. movie projector; 4. control panel; 5. digital computer; 6. analog computer; 7. recorders; 8. main control panel.

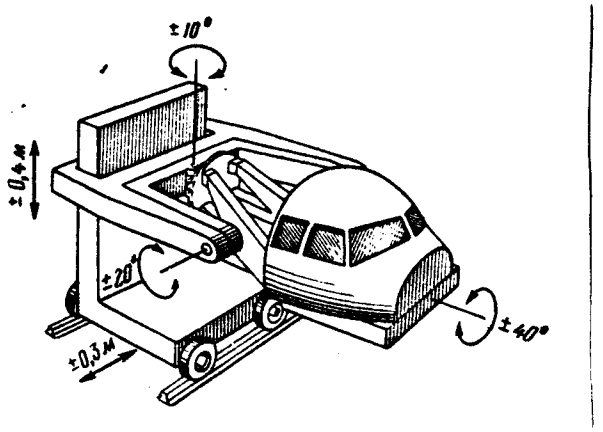

Fig. 4.8. General view of mobile five-stage platform.

A dynamic piloted AC simulator, reproducing the dynamics of flight, has been developed abroad. The visual and acoustical flight situation is simulated in it, and various accelerations, which act on the crew, are reproduced [13, 25]. /268

The equipment included in the simulator is shown in Fig. 3.8, and a general view of the mobile platform, having five degrees of freedom, is represented in Fig. 4.8.

The situation is reproduced in the visualization system of this trainer by means of an image on the screen of a cathode ray tube, which is projected on the cabin window through a collimator. An image of a perspective view of a runway is projected on the inner surface of the canopy, by means of a projector installed in the cabin. By movement of the runway picture, the pilot receives altitude and course data relative to the movement, the aircraft location, its speed, bank and pitch. One of the simulator computers is designed

to switch into the repetition mode. This mode permits the simulation to be carried out on a shortened time scale and, owing to the high frequency of repetition, observation of a continous picture of the effect of change in parameters and selection of the optimum conditions. The simulation of wind gusts and other stochastic processes affecting the operation of the control system is accomplished by generators, which are uncorrelated sources of white noise.

In a trainer for supersonic aircraft pilots, the cockpit, /269
set into a cantilever 7.3 m long, can be moved more than 6 m in the vertical plane and 2.4 m in the horizontal, and turned relative to the center of mass at a ±45° bank, ±30° yaw and ±5° pitch. The movements and turns of the cockpit can be produced by a program fed into the trainer memory.

Flight Trainers

Development of flight trainers proceeds from the rule which states that the pilot must be taught in the trainer, not to fly in general, but to fly in a given type of aircraft, i.e, to learn how to fly a specific machine. Therefore, flight trainers, as a rule, include a full-scale model of the cockpit of an actual aircraft, usually installed immovably in the classroom. Actual controls and flight-navigation instrument simulators are placed in the cockpit. The flight trainer should, in a calculated manner, determine the behavior of the aircraft caused by the actions of the pilot and external causes, inform the pilot of the flight mode and reactions of the aircraft to the pilot actions by means of the onboard instrument simulators and sensory effects which usually act in flight, and produce a sufficiently detailed, accurate and continuous record of the course of the exercise, in order to decide on the correctness of the trainee actions. For these purposes, special computers and an instructor panel are included in the trainer. As a rule, the following are placed in the instructor panel:

1) duplicates of the instrument simulators in the trainer cockpit;

2) levers for introduction of certain factors, changing the flight conditions (wind speed and direction, air turbulence, icing, change in position of the center of gravity, amount of fuel and freight at takeoff, barometric pressure, external air temperature and other things);

3) failure panel, for introduction of failures in systems and instruments (engine failure, oil pressure drop, landing gear damage, fire, unpremeditated reversing of the propellers, generator breakdown, failure of hydraulic system units, breakaway into /270

a spin, fuel pump failures, wheel brake failures, booster failure, radio compass cutoff, static line out of order and other things);

4) system for recording flight parameters and nature of execution of the flight program by the pilot.

Although the pilot's perception of bank and pitch acceleration are not reliable sources of data in an actual instrument flight, they still play an important part.

Reproduction of G-forces in the trainer can be accomplished by means of installation of the trainer cockpit in a centrifuge. Simulation of the actions of G-forces in the trainer can be created by way of use of:

a special suit, worn by the trainer, in which the required pressure can be created on the abdomen, arms and legs;

systems of levers and cables having a specific action on the pilot.

illusions of the action of G-forces without application of all the forces also can arise in the trainee:

by means of supplying electrical impulses to certain parts of the nerve endings at the base of the skull;

by means of creation of an appropriate moving panorama of the surrounding terrain. This illusion can be reinforced if the trainer cockpit has the ability to turn to restricted angles with properly selected angular velocities.

However, all these methods have not found any sort of widespread use in aviation trainers, for a number of reasons.

For an approximate simulation of the sensations of an operator, connected with the action of accelerations, a system for turning the cockpit around two axes is widely used in trainers. By means of suspension of the cockpit on a universal joint, various vertical accelerations during limited periods of time can be simulated. Upon going into a coordinated turn, the cockpit is turned by the magnitude of the bank angle, determined by a computer. In order to avoid the sensation of an uncoordinated turn, the cockpit is rotated in the horizontal position, at a speed which is imperceptible to the pilot. In coming out of a bank, the /271
cockpit is turned in the opposite direction and again is slowly rotated in the horizontal position. In this manner, the pilot physically perceives the bank acceleration, which is very important to him.

The actual pitch angle is presented in the form of turning the cabin around the transverse horizontal axis. Different

longitudinal accelerations are reproduced by pitching turns, so as to create the illusion of a turn in the gravity vector.

Linear accelerations also are subject to simulation. Forward accelerations can be simulated if the cockpit is installed so that it can be deflected ahead like swings and held in this position. Then, the pilot will feel pressure on the back and perceive this as the result of the action of the forward acceleration, as long as the instruments or some visual effect maintain this sensation.

A similar lateral movement can be made, for simulation of the action of lateral accelerations, for example, during an improper turn.

Specialized Trainers

Visual Takeoff and Landing Trainers

These trainers are used for training pilots in visual "takeoff" and "landing." A film strip sometimes is used for these purposes, in which the terrain scanned by the pilot during takeoff and landing is photographed. The image of this terrain should be moved vertically and horizontally on this screen, within the limits and with the speed, which are necessary for simulation of a visual takeoff or landing.

The following elements are basic to simulation in any system of visualization: linear perspective, movement, image sharpness and features of the visibility conditions from the air. The linear perspective of the image provides the primary part of the visual illusion of flight. It usually is connected with transformation of points in three-dimensional space from a system of stationary coordinates to their perspective representation in the picture plane, normal to the longitudinal axis of the AC. Solution of /272
the equations for transformation of points to their perspective images can be carried out either physically, with the aid of scale models, or mathematically, with the aid of computers. Aside from dependence on the method used in composition of the visual situation imitator, devices providing the following should be included:

1) storage of information on the visual features of the region of the simulated flights;

2) selection of information on the part of the region being flown over at a given moment;

3) transformation of points in three-dimensional space from the stationary coordinate system to their perspective representations;

4) image transmission.

A schematic diagram of the optical system of a visual situation simulator is represented in Fig. 5.8. Storage of data on the flight region is accomplished by means of a color slide; selection of the section being flown over is carried out by means of moving and turning the color slide in the projector beam; construction of the perspective image takes place in a mobile television camera, and transmission of the image is provided by a television cable and projector, which projects the picture on a screen in front of the trainer cockpit. The color slide is moved in two coordinates x, y, in accordance with the route of the simulated flight, and it is turned in the projector beam at an angle, corresponding to the present heading. For simulation of visibility conditions, there is a diffusion filter, which can be inserted by the instructor into the projector beam to different depths, which leads to washing of the image at a given distance. The projected image of the terrain has a scale of 1:900, and the image size is 3.6 m.

The television camera, with a vidicon type tube, is moved to the bank and pitch angles, as well as in the direction perpendicular to the plane of the projected image, so as to simulate changes in the flight altitude. Displacements in altitude are carried out on a scale, corresponding to the scale of the projected image. The camera has a f1/14 lens, selected to obtain maximum sharpness. The near sharpness limit corresponds /273
to 100 mm, which, at the scale of the projected image selected, corresponds to a distance of 90 m on the ground. The perspective image of the terrain accepted by the television camera is transmitted to the screen by means of a television system (6000 lines per frame).

However, more complicated systems are used for simulation of an actual visual takeoff or landing. Let us examine one of these possible systems of takeoff and landing simulation with visual orientation.

The system includes a three-dimensional runway model and the /274
terrain adjoining it, prepared on a certain scale, with all characteristic details.

By means of a scanning survey of the model by a television camera, placed so that it "represents" the eyes of the pilot, and subsequent projection of the image on a large screen, about 4.5 m wide, installed in front of the trainer cockpit, it is possible, with a great degree of similitude, to produce a simulation of a takeoff and a landing with visual orientation. Keeping in mind that the eyes of the pilot are continually moving with the aircraft, by means of signals, characteristic movements of the aircraft and computer-generated longitudinal movement can be

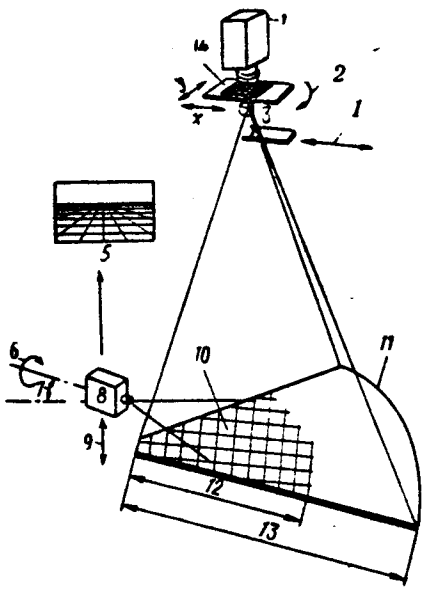

Fig. 5.8. Schematic diagram of optical system of visual situation simulator: 1. projector; 2. change in heading; 3. lens; 4. diffusion filter; 5. image on screen in front of pilot; 6. change in bank angle; 7. change in pitch angle; 8. television camera; 9. change in altitude; 10. terrain image; 11. model screen; 12. visibility distance; 13. maximum visibility distance; 14. color slide.

caused, and it moves towards the television camera in an appropriate manner.

The television camera control system will produce aircraft movement with six degrees of freedom in this manner. In this case, longitudinal movement of the camera will be accomplished by means of moving it on a cart on rails along the runway model; lateral movement is by means of lateral displacement of the camera relative to the cart. Flight altitude must be simulated by raising or lowering the camera relative to the runway model. The camera is mounted so that its optical axis is directed vertically with respect to the runway. By means of a hinged mirror, inclined at an angle of approximately 45° to the optical axis of the camera and directed along the runway model, it is possible to simulate a change in pitch angle, by means of turning the mirror on the hinge, the axis of which is parallel to the axis of the aircraft.

Change in heading is simulated by means of turning the camera and mirror about the axis perpendicular to the runway surface. Banking is simulated by turning the camera around its optical axis.

The necessary depth of definition of the runway image is produced by means of using small objective diaphragms and appropriate illumination, insuring sufficient brightness of the image on the camera tube.

Astronavigation Trainer [22]

A trainer has been developed for training and instruction in aircraft guidance by navigator personnel, under conditions of high latitudes and a great range of flight altitudes and speeds. It is a spherical segment, limited in the scale chosen to 25° North Latitude. The inside diameter of the spherical segment is 11.33 m. The girder of the spherical segment frame has a universal joint /275

suspension, providing two degrees of freedom of movement, and it permits navigation problems, connected with flight in any direction, to be solved.

Over 500 small lamps are installed in the housing girders, the locations of which give an accurate picture of the starry sky in the northern hemisphere, with 31 constellations.

The trainer permits simulation of flight with speeds of up to 2800 km/hr, in any region of the Arctic, including the region of the North Pole.

Rotation of the housing with the required speed is accomplished with the aid of a small, 1.15 hp electric motor, through a reducer with a high gear ratio of 120,000:1. The minimum rotation speed of the sphere is 0.000694 rpm and the maximum, 0.005 rpm (or 7 revolutions per day).

The trainer permits simulation of flight along the great circle route through the polar regions, to a distance of more than 10,000 km. Control of mechanisms of the unit is exercised from the instructor panel. The role of the instructor in control of the test unit is similar to the role of the pilot in actual flight. Like the pilot, the instructor is also in continual contact with the navigator and, receiving data from him, depending on the navigation problem set, creates the provisional flight parameters in the unit, by means of electrical control point adjustments on the control panel.

During the "flight" the instructor can insert changes in the initially assigned conditions, for example, to change the wind direction and speed, air temperature and pressure and the like. In accordance with the changed conditions, the trainee refines the calculation of the flight along the course and transmits the new data to the instructor.

The instructor introduces corrections on the master panel, and the computers automatically transform the signals received to the specified type of movement of the celestial hemisphere, artificially, but precisely, simulating the movement which the navigator would observe during an actual flight along the assigned course. Simultaneously with movement of the canopy, recorders are started, tracing the flight path on a map of the surface of the earth, installed in the instructor panel. /276

In addition to that, the values of all the primary flight parameters are continuously transmitted to the instructor panel: air and route speeds, barometric altitude, true heading, aircraft course, wind direction, latitude and longitude of the aircraft position.

Radar Trainer

The radar trainer, being a simulator of a panoramic radar, is intended for solving problems connected with:

evaluation of operators in observation and "reading" the terrain survey images on the radar station display screens;

evaluation of the subjective qualities of the operators and tactical-technical data of the radar station [22].

The trainer consists of a tank of distilled water, in which a contour map of the surface of the earth, usually at a scale of 1:200,000 (2 km per mm), is immersed. The water temperature is maintained constant. A mock-up of a radar antenna is placed above the map and below the surface of the water. It can be moved to any position relative to the map from the control panel. This antenna simulates an aircraft flying over a given terrain. The antenna radiates ultrasound pulses, the propagation rate of which in water is 0.000005 of the rate of propagation of electromagnetic waves in air. The ultrasound pulses radiated by the antenna are reflected from the map contours, and are received and converted into radar pulses, supplied to the panoramic radar screen. The effect of interference on the operation of the radar simulator can be simulated from the instructor panel.

Concerning integrated trainers, as has already been pointed out, they are an actually operating model of the cockpit of one aircraft or another, and they include both the specialized and flight trainers discussed above.

Astronaut Training Trainers

Development of professional skills in control of a craft and its systems in astronauts and preparation of the body of the astronaut for the conditions of space flight require the use of a specific set of training means. /277

By virtue of the fact that a training spacecraft, intended for astronaut flight training is not yet built, requirements for astronaut ground trainers must be unusually complex. In these trainers, space flight conditions and factors and emergency situations should be simulated, the operation of separate systems and the flight dynamics should be modelled and development of the necessary work skills in the astronauts should also be provided.

Ground training of spacecraft crews for professional work, thus, still is the primary form of their training [20, 25, 27, 57]. This circumstance mainly determines the fact that space trainers should be built before accomplishment of the first flight of one

craft oranother. More than that, space trainers permit their use for working out medical-technical requirements for control systems of the craft and their equipment being developed, with account taken of the psychophysiological capabilities of the operator, right during the process of development of the craft themselves. Such a variety of trainers, in which investigation of control systems with operator participation is carried out, can be called a dynamic test unit-trainer. In proportion to completion of development of control systems of the craft and of its equipment, the dynamic test unit-trainer has the possibility of becoming a total trainer, as it were.

There are the most diverse opinions at this time as to what types of trainers are necessary for training astronauts in professional work. For example, one of the American specialists considers that it is most advisable to use a universal, single trainer for all craft for astronaut training [25, 27].

There are very diverse training means, according to their purpose, tasks worked out in them, effectiveness of their influence on astronaut training, as well as according to the construction produced.

The basis of a trainer system requires the conduct of analysis of astronaut activities during flight in various types of craft, determination of the group of tasks applicable to working out in /278
trainers and analysis of trainers, from the point of view of their effectiveness in formation of appropriate operator skills. Therefore, the necessity arises for training spacecraft crews on the basis of trainer systems. The basis and adopted systems of trainers are very important for determination of the quantity and sequence of commands in trainers. The classification of trainer facilities should be examined, for a clearer idea of trainer facilities and the basis for trainer systems. A classification scheme depends on the classification characteristics adopted (Fig. 6.8).

According to type and nature of astronaut training, all training facilities can be divided into trainers and facilities for preparation of the astronauts' bodies for space flight conditions and trainers for development of professional skills of the astronauts in control of the craft and its systems.

Besides this, there can be integrated trainers, in which astronaut training for professional activity in a spacecraft is carried out in combination with preparation of the astronauts' bodies for the extreme conditions of space flight.

The first group can include trainers and facilities for physical and special training (Fig. 7.8) and trainers-simulators of the environment and space flight conditions (Fig. 8.8).

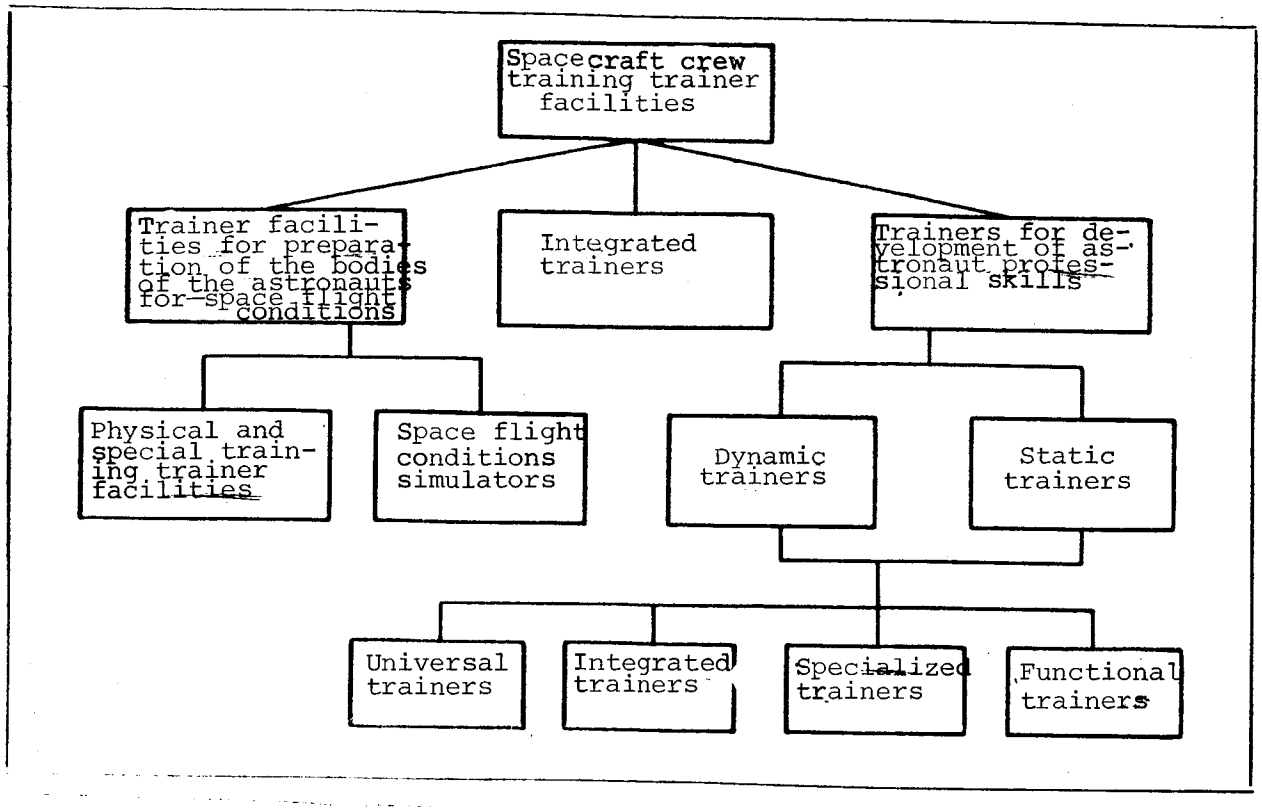

Fig. 6.8. One possible trainer facility classification scheme.

We shall dwell below more in detail on only the second group, trainers for development of professional skills in control of a craft and its systems.

Depending on the influence on the human body of movement factors, these trainers can be dynamic or static. Dynamic trainers are devices in which the cockpit or workplace of the operator being trained moves in accordance with the simulated dynamics of the craft. Thus, in dynamic trainers, such factors as angular velocity and angular and linear accelerations act on the human body. The cockpit is stationary in static trainers.

Depending on the size of the simulated system, flight stage and simulated tasks, trainers for development of professional skills of astronauts can be universal, integrated, specialized or functional (Fig. 9.8). /281

The universal trainer is a single, multipurpose trainer, intended for training of crews of various types of spacecraft.

The universal trainer is an extremely complicated arrangement, the characteristics of which can be changed and adjusted, in conformance with the characteristics of different planned or existing spacecraft. The most important components of such types of universal trainers are: mobile or stationary spaceship cabin model, computer,

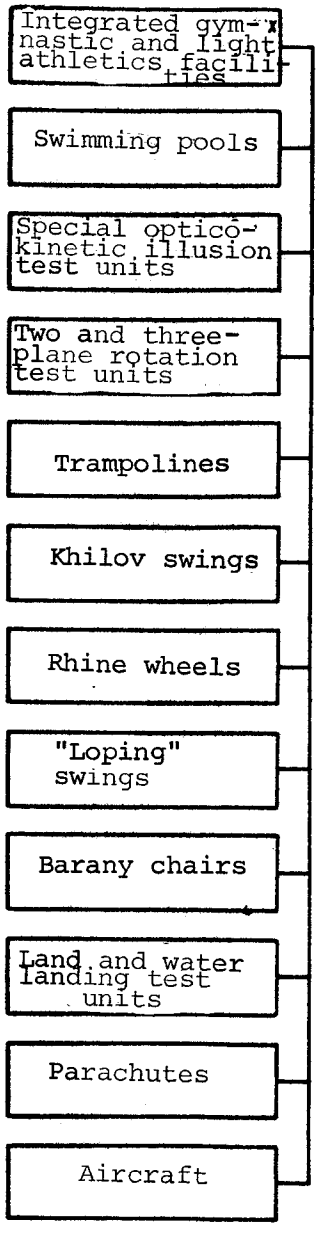

Fig. 7.8. Trainers and facilities for physical and special training.

instructor panel, sky and earth surface simulator, programming device and recording apparatus.

There can be a cabin or chamber in the universal trainer complex, in which temperature regime, rocket noise, vibrations, gaseous environment, pressure, humidity and air circulation are reproduced and certain other flight conditions of the corresponding spacecraft are simulated.

In addition, the universal trainer should include systems which are common to different spacecraft, such as controls of spacecraft position in space (pitch, yaw, rotation), navigation and others.

The integrated trainer is a trainer which provides training for all crew members for activity in a specific type of spacecraft at all stages of flight.

It satisfies the requirements for a universal trainer, but, in addition to this, it is equipped with all systems, instruments and apparatus, which should be in the corresponding spacecraft.

The specialized trainer is a trainer which is intended for developing skills of a set of specific work operations, which are necessary for accomplishment of special tasks of a future space flight.

Members of the crew have to improve skills in the use of certain systems, intended for accomplishment of one or more flight tasks in specialized trainers. For example, there can be the following specialized trainers: craft orientation, navigation, craft control during change from /283 orbit to orbit, approach and rendezvous with a space station, as well as mooring to it, carrying out assembly and repair of a space station or craft in orbital flight, landing the on earth, control of operation of the life support system, work with research apparatus installed in the craft, and other things.

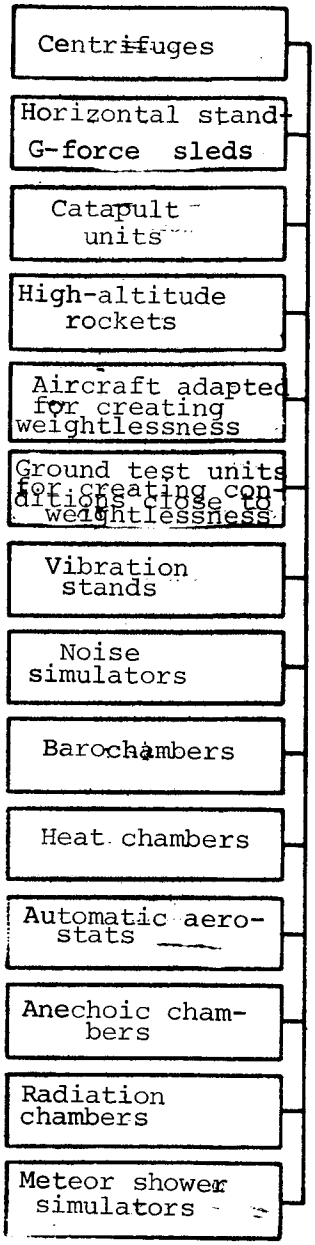

Fig. 8.8. Space flight conditions trainers-simulators.

Of all the diversity of tasks to be put into practice in a special trainer, one or more tasks is taken and only the system and information sources which are used by an astronaut in executing these tasks are simulated.

A functional trainer is a trainer intended for developing skills in carrying out work operations of one type or for training of individual functions of a man, such as tracking, attention and others. Precise simulation of any specific system with which the operator works is not required in a functional trainer. It should simulate only what is necessary for increasing the functional capabilities of a man in a given type of activity.

As was pointed out above, it is possible in principle to create an integrated trainer, in which training of astronauts for professional activity in control of a spacecraft and its systems is carried out in combination with preparation of the astronaut's body for the extreme conditions of space flight.

In order to build such an integrated trainer, computers simulating the dynamics of the flight of the craft, simulators of all of its systems and all equipment, as well as simulators of the environment and conditions of space flight must be combined in one arrangement. This task is difficult to accomplish, and it requires expenditure of great resources. Partisans of the main extreme opinion pose the question of creating a trainer, which would simulate, not only some one spacecraft, but would provide for simulation of several types of craft, reasoning this from the fact that spacecraft have many common characteristics and that the differences between them are unimportant.

Training of an operator in functional trainers provides high- /284
quality and rapid development of individual skills, since, during the training, the attention of the operator is distracted less from the specific activity assigned. Besides, functional trainers are simple, cheap and have a high throughput capacity. Therefore,

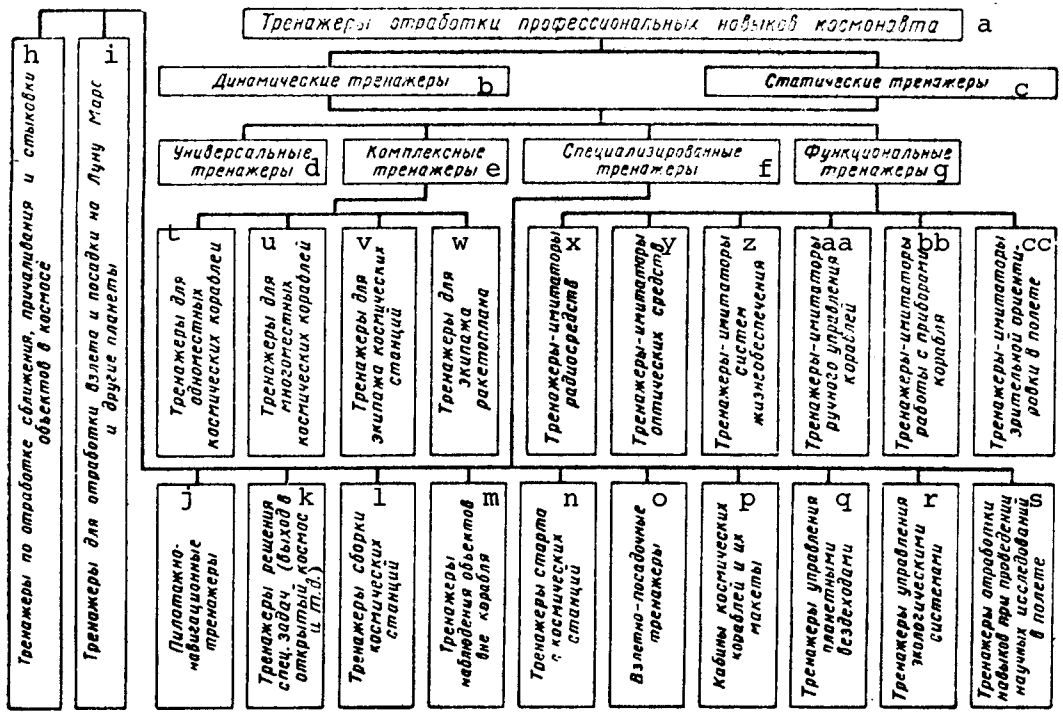

Fig. 9.8. Classification of trainers for developing astronaut professional skills. /282

Key: a. Trainers for development of professional skills; b. Dynamic trainers; c. Static trainers; d. Universal trainers; e. Integrated trainers; f. Specialized trainers; g. Functional trainers; h. Trainers for perfecting approach, mooring and docking of objects in space; i. Trainers for perfecting takeoff and landing on the moon, Mars, and other planets; j. Flight-navigation trainers; k. Trainers for solution of special problems (extravehicular activity, etc); l. Space station assembly trainers; m. Trainers for observation of objects outsidecraft; n. Trainers for launch from space stations; 0. Takeoff-landing trainers; p. Spacecraft cabins and their models; q. Planetary cross-country vehicle control trainers; r. Ecological systems control trainers; s. Trainers for perfecting skills in conduct of scientific research in flight; t. Single-seat spacecraft trainers; u. Multi-seat spacecraft trainers; v. Space station crew trainers; w. Rocket aircraft crew trainers; x. radio equipment trainer-simulators; y. Optical equipment trainer-simulators; z. Life support system trainer-simulators; aa. Craft manual control trainer-simultors; bb. Craft instrument operation trainer-simulators; cc. Flight visual orientation trainer-simulators.

for development of skills which require the greatest number of training hours and of certain particular skills, in which it is especially difficult to achieve perfection, it is advisable to have functional trainers.

However, the operator in a spacecraft, in the process of carrying out a specific type of activity, for which he is trained in a functional trainer, in addition, has to observe data coming in from other onboard equipment and intervene in the operation of other systems, which are not directly connected with carrying out this type of activity. An operator who is unprepared for this may not fulfill the assigned missions and he will accomplish even those operations for which he was trained in a functional trainer poorly and with insufficient precision.

Therefore, final development of skills in accomplishing specific operations must be carried out in specialized and integrated trainers, in which the actual conditions of operator activities in space flight are more fully simulated. In this case, specialized trainers provide operator training for carrying out a specific group of tasks which are necessary in flight. Multiple trainers provide the operator with the possibility of "acutely feeling" more fully the amount of work in a spacecraft, the sequence of operations from takeoff to landing, and of learning possible emergency situations and failures of individual units and systems, etc.

Even a brief examination of the tasks to be carried out in different types of spacecraft and the characteristics of the objects of control shows their great diversity. Reproduction of the characteristics of different objects of control, changing within wide limits, and simulation of the work of all spacecraft systems makes a universal trainer, bulky, costly and of low efficiency. Moreover, in future mastery of space, the number of different craft will increase and the throughput capacity of the universal trainer will not provide for the needs for training crews of various types of spacecraft. /285

For full-value training of astronauts (as well as for conducting scientific research work, directed towards study of efficient methods of display and signal indication, manual and semiautomatic control systems and the composition of spacecraft equipment), there must be three types of trainers: integrated specialized and functional. Such a system of trainers guarantees effective training of an operator for professional activity under space flight conditions.

In the process of training astronauts for professional activity in trainers, for a number of reasons, the necessity can arise for their preliminary training in simplified, specialized trainers, not completely corresponding to the actual onboard

control systems. This can be required during both preliminary training on earth and during training on onboard space trainers, under conditions of a long space flight.

In particular, there is practical interest in certain problems, connected with investigation of permissible changes in the types of displays in models of control systems of an item in specialized trainers, relative to the type of display of the onboard system specimens themselves. Would not such a simplification lead to development and reinforcement of unfavorable skills in the operator or, on the other hand, would it assist him in forming and transferring skills during work with an actual system?

Normally, such questions arise during development of medical-technical and psychological requirements for trainers and while proving methods of preparation and training of operators for professional activity.

Experimental data examined below permits a judgment to be made on the possibility of simplification of the display type by simulating control systems of slowly occurring orientation processes. Two groups of operators took part in the research: primary and control.

The primary group of operators formed skills in manual control of orientation of a specified object in a simplified simulation test unit, using analog computers and a special instrument outfit, reproducing a simplified system for needle indications of angular positions and angular velocities of the AC, in the course of training exercises. Operators of the control group not participating in this training did not form such skills. /286

Then, both groups carried out manual orientation of a controllable object in a model AC cockpit, using an indicator in the form of the "Look" optical indicator.

In this case, in both indication systems (the simplified and the onboard), the dynamics of the manual control process were identical.

A large number of experiments, grouped into two series, were carried out. In the first series of investigations, a control system with a three-channel onboard handle was used, and in the second series, one with a special key panel. It was determined in preceding investigations that the system with the key panel causes less stress on the operator than the system with the three-channel onboard handle. The results of the activities of operators, previously undergoing training in AC orientation in a simulation test unit, with the simplified display system, proved to be better, both in the first and in subsequent experiments, than the results of activity of the control group of operators.

Thus, after the first training experiment, the craft orientation time for the control group of operators, using the three-channel handle, was greater by 20% on the average than for operators of the primary group, in the amount of correlated errors in orientation by 50% and the number of erroneous actions by 70%. In subsequent investigations, the quantitative and qualitative results of work activities of operators of both groups improved. However, they still remained poorer in the operators of the control group, even in the final investigations (10th experiment), namely, orientation time was greater by approximately 8%, number of errors by 32%, number of erroneous actions by 64%, fuel consumption by 18%, etc.

A similar picture also was observed in a comparison of quantitative and qualitative results of work activities of operators of the primary and control groups, during work in the orientation control system using a key control panel [29, 30]. /287

The experimental research results presented show that the nature of the operator activity in man-machine systems, his reliability, as well as the output parameters of this system, are determined to a great extent by the type of display devices and the number and structure of the parameters reflected. These data once again emphasize the importance and practical value of specific engineering-psychological investigations for planning control systems and for proving methods of training operators for professional activity.

The limits of simplification of equations describing the movement of a controllable object should be considered in each specific case, in development of one trainer or another. These simplifications are useful, since they lead to a reduction in the complexity of the structure of the trainer computer, and this means, in its cost.

However, it must be taken into account that, in a number of cases, these simplifications can be undesirable, since such a trainer can inoculate the operator with wrong habits and, thereby, he will not satisfy his primary purpose.

There also is interest in the question as to what extent the biological environment, in which the operator will be and work in the craft, must be simulated in trainers.

The results of comparative investigations on transmission and reception of data have shown that there is no basis for simulating the biological environment in a professional trainer; therefore, the trainer cabin can be made unpressurized and actual onboard life support systems need not be used in it.

In concluding this section of the chapter, let us examine an exemplary block diagram of an integrated spacecraft trainer (Fig. 10.8) for training of astronauts in professional activity [27].

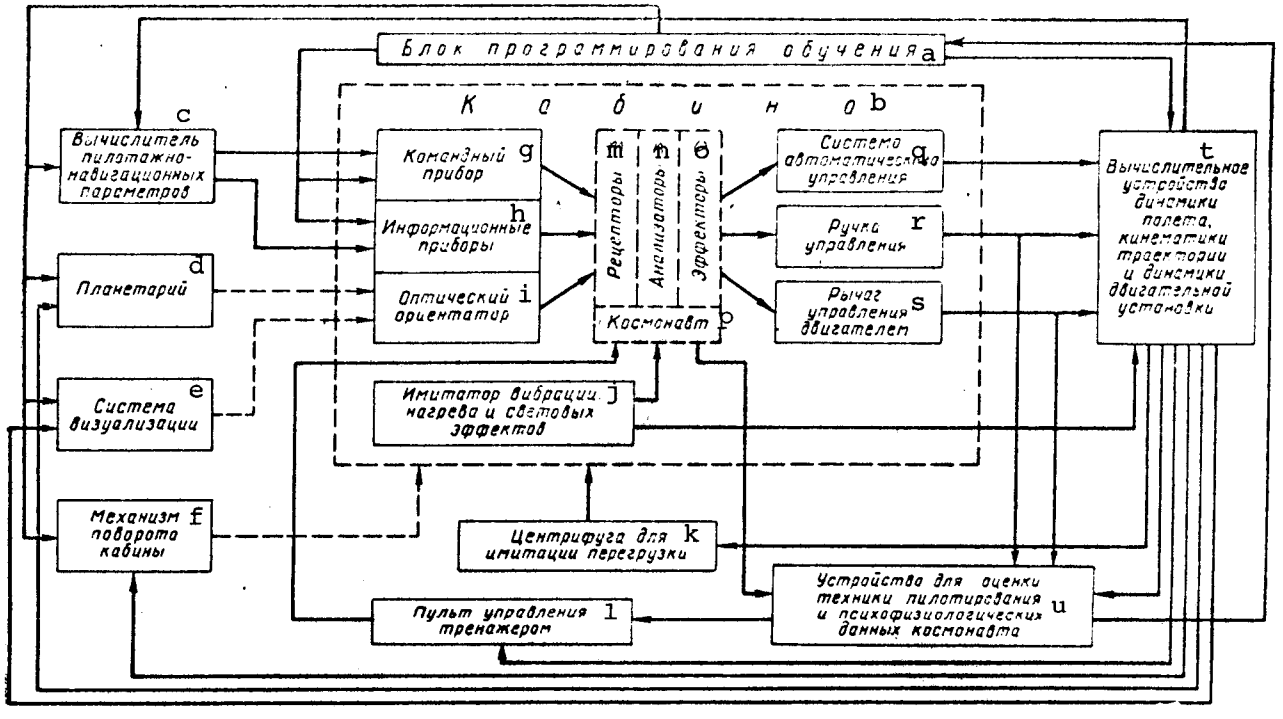

Fig. 10.8. Approximate block diagram of integrated spacecraft trainer. /289

Key: a. Instruction programming unit; b. Cabin; c. Flight-navigation parameter computer; d. Planetarium; e. Visualization system; f. Cabin turning mechanism; g. Master instrument; h. Information instruments; i. Optical orientor; j. Vibration, heat and light effects simulator; k. G-force simulation centrifuge; l. Trainer control panel; m. Receptors; n. Analyzers; o. Effectors; p. Cosmonaut; q. Automatic control system; r. Control stick; s. Throttle lever; t. Flight dynamics, flight path kinematics and power plant dynamics computer; u. Equipment for evaluation of flying techniques and astronaut psychophysiological data.

The trainer has to have a craft cabin mock-up with simulators of all onboard instruments and actual controls, must simulate the dynamics of angular movements and the kinematics of the flight path, simulate the visual flight situation and the influence of external factors and disturbances in all stages of the simulated flight, from takeoff to landing. Analysis shows that it is not expedient to simulate the flight conditions of an astronaut during prolonged weightlessness, or under G-forces as well, in an integrated trainer. The latter usually are created only in specialized trainers. /288

Simulation of the flight dynamics and flight path kinematics and of the operation of the primary instrumentation is accomplished by means of inclusion of an analog computer in the trainer [20].

The visual flight situation has to be reproduced in the trainer, with the aid of a planetarium and projection system. Control of the planetarium and projection system must be carried out from the electronic model, with account taken of the craft orientation as to pitch and yaw angles, rotation and its movement over the surface of the earth. The trainer has to be provided with equipment for recording the flight parameters, deflections of the controls, time and quality parameters of the vocal and motor reactions of the operator, and recording and analysis of the physiological functions of the operator.

For provision of programmed instruction of the astronauts, the trainer has to include a programming unit and equipment for objective monitoring and evaluation of the readiness of the astronaut.

Ye. A. Karpov [48] has discussed special biomechanical training of astronauts in trainers with unstable supports. The task of these trainers was to prepare an astronaut going into space for the new, unusual situation, teach him to construct an arbitrary orientation system ("up-down") in different cases and to change the position of his body as desired, using the laws of biomechanics. The training program included: familiarization with the motor capabilities of man in an unsupported position; development of sensory skills of control of the angular position of his body in unsupported space, with the aid of the body; development of stable coordination of movements during different movements in an unsupported position.

Training in the "unsupported" trainer resulted in the perfection of three tasks overall:

"Orientation " -- occupy an assigned position of the body, with the longitudinal axis at an angle to the horizontal plane, by means of change in lcoation of the center of gravity and pulling on a halyard (Fig. 11.8). /290

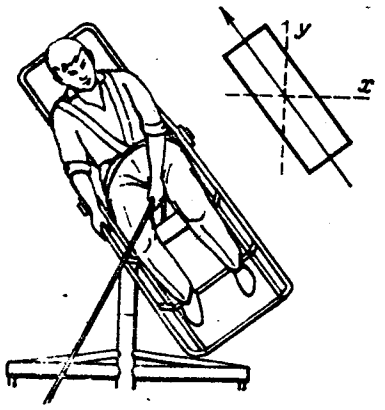

Fig. 11.8. "Orientation" (from Ye. A. Karpov).

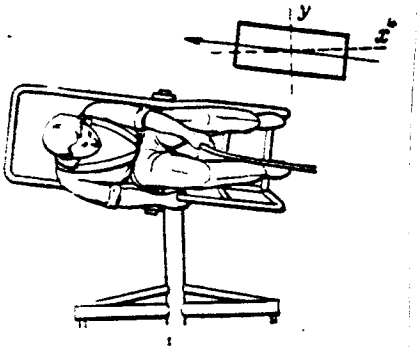

Fig. 12.8. "Stabilization" (from Ye. A. Karpov).

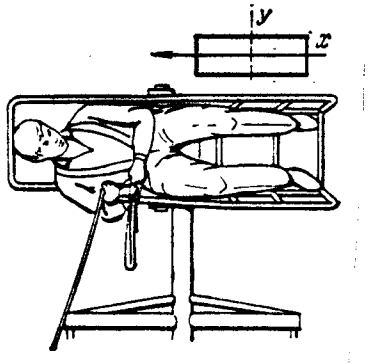

Fig. 13.8. "Swims" (from Ye. A. Karpov).

"Stabilization" -- maintain assigned position of the body, with the longitudinal axis at an angle to the horizontal plane, balancing the center of gravity and pulling on a halyard, overcome, in this case, additional "random" forces, created by the instructor, which complicate the assigned orientation and stabilization of the body in space (Fig. 12.8);

"Swims" -- move to an assigned place, together with the test unit (forward, to the side), by means of pulling on the halyard, maintaining (stabilizing) the assigned, unusual position of the body in space while doing so (Fig. 13.8).

Each astronaut preparing for flight completed all three training tasks, executing them 118-120 times in all. /291
In evaluating the quality of execution of each training task, the following were taken into account:

nature, duration ($\Delta\tau_i$) and magnitude (Δd_i) of deflections of the longitudinal axis of the body of the trainee from the assigned position;

total time spent in carrying out the exercises (t_t).

As an illustration of how training in the "unsupported" trainer facilitated development of the necessary sensory motor habits, data obtained on A. A. Leonov, as he executed a turn of the body from the vertical position to the horizontal, are presented. The corresponding characteristics are shown in the graph (Fig. 14.8)

The results of the first training session of the astronaut are represented by the two flatter lines, and the results of the eighth, last training session, by the two steep lines. Comparing these data, it is easy to see that it was several times more difficult for A.A. Leonov

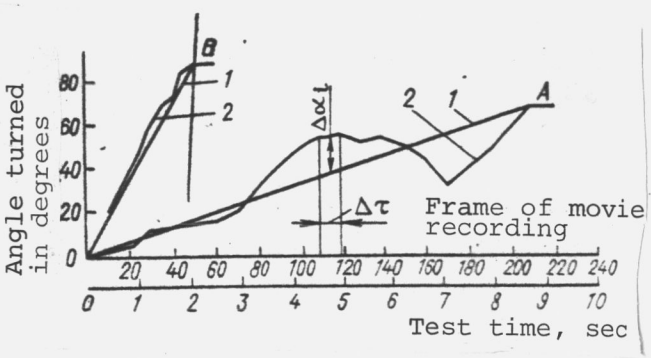

Fig. 14.8. Characteristics of orientation performed by A. A. Leonov in the first (A) and eighth (B) training sessions: 1. required pattern of movement, 2. actual pattern of movement (from Ye. A. Karpov).

to accomplish "orientation" -- take the assigned body position (from the initial vertical) -- in the first training sessions than in the last. Initially, an excessive degree of freedom of the moving organs was noted in him and the entire "orientation" process lasted up to 8-9 sec, and, at the end of the training sessions, A. A. Leonov, having converted this task into a well-controlled system, began to accomplish it in 2 sec.

By the end of the training, /292 the astronauts executed all these three types of tasks sharply, quickly and firmly.

Analysis of the data obtained during these training sessions permitted the corresponding criteria $\Delta\tau_i$, Δd_i, t_t to be compiled, which made it possible to objectively characterize the activity of an astronaut in carrying out a portion of the flight program.

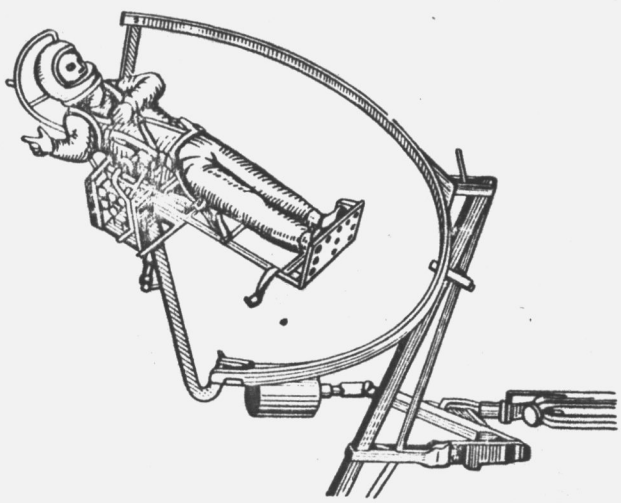

Fig. 15.8. Astronaut in trainer with unstable support.

One of the types of trainers with an unstable support ("unsupported test unit") is presented in Fig. 15.8.

Progress in Formation of Skills and Method of Evaluation of Training of an Operator During Work in AC Control Systems in Trainers

The complexity and diversity of tasks, which an operator carries out in control of AC systems, requires great mental and emotional effort of him and his preliminary training for professional activity. It is evident that, in the training process, the body of the operator adapts itself to the nature of the operation of

the object controlled or process controlled. The operator acquires and fixes the necessary skills in control of the systems and, on the whole, a trained operator resolves the control task with less expenditure of energy and establishes better coordination in the operation of various systems. /293

In solving the problem of "adaptation" of the operator to systems controlled by him, the problem arises of determination of progress in formation of control skills by the operator and the level of his training. Solution of this problem permits proper substantiation of the method of training an operator for professional activities and makes it possible to select the best trained from among many. A large number of investigations have been devoted to the problem of skill. One of the most significant features of a skill is the connection between the dynamics of its formation and the dynamics of change in the emotional strain in the course of the training,without revelation of which it is impossible to reveal the psychic nature of the skill. As is well known, the basic position of psychology on skill is the assertion of the fact that a skill is the realization of the activity of the operator, brought to a known degree of perfection, easily accomplished, rapidly, precisely, economically and with the highest qualitative and quantitative results [69]. The rate of formation of working skills in an operator depends greatly on the type of occupation and has unique differences. Thus, for example, the unique feature of the skills of an astronaut in control of a ship and its systems are:

a pronounced lability and plasticity of skills in the work of an astronaut, under conditions of time deficit and excess;

the unusualness of the task under flight conditions and responsibility of the crew members for accomplishing it;

rapid distribution and switching of attention, under conditions of dynamic orientation in time and space, in detection and maximum differentiation of signals in the course of control of the ship's systems;

the probability of a certain fading of working skills during prolonged space flights, under conditions of a monotonous situation;

heightening of emotional stress upon perceiving a feeling of prolonged isolation;

the effect on the body of an astronaut of the unusual conditions of space flight, in which the central nervous system, by means of rearrangement of the emotional and vegetative reactions, /294

has to provide, not only for activity of the working organs, but compensate for the unfavorable effect on the body of the unusual conditions of the external environment [27].

Also well known are the fixed and highly specific conditions of activity of a pilot in modern supersonic aircraft: deficit of time in executing primary combat missions, as well as tasks during takeoff, landing, and aerial refueling; emotional excitement in carrying out high altitude and high speed flight;[1] considerable G-forces during various evolutions of the aircraft; constraint of movement during use of a high-altitude pressure suit or space suit, and other things.

The evaluation of the level of training of an operator used up to now, as to time charactertistics and magnitude and number of errors committed in the process of control, is not sufficiently complete and objective. In this case, only the output quantities of the dynamic "link" are considered which represent the element of participation of the operator in control. True, sometimes, certain physiological indicators, which can give an idea of the magnitude of the physical and emotional stress on the body in the process of control work, are evaluated quantitatively. For a more complete disclosure of the psychic nature of skills formed, the degree of reorganization of the indicators of the neuropsychic domain of the operator, from the EEG, EMG, EKG, GSR and PG, must be taken into account.

Thus, in research carried out using multiple recordings of the physiological functions [7], it was determined that, in proportion to formation of working skills in control of a manual orientation system of a spacecraft, beginning with the first training exercise, a reduction in the bioelectric activity of the high frequency rhythms of the cerebral cortex (from 17.3 to 11.8 integral units), a reduction in the bioelectric activity of the muscles (from 132 to 82 μV), a decrease in the amplitude of galvanic skin potentials (from 610 to 380 μV) and in heart rate to values close to the pulse rate in a state of rest, are observed. /295

However, only this evaluation of the training of an operator will be incomplete. It should be taken into account here that inside a living organism, a number of physiological systems are functioning and, therefore, it must be possible to evaluate the coordination of the operation of individual systems quantitatively, so that, on this basis, an objective conclusion can be drawn as to the quality of the work of an operator in the overall man-machine system.

[1] The circumstance must be taken into account that a moderately marked emotional excitement stimulates and improves the simpler skills and skills which are automatically performed, but impairs the more complex and less developed ones.

The dynamics of change in the quantitative evaluation of the work of various systems of the body of the operator, as well as coordination within individual systems during training, permits timely determination of the arrival of the moment when the operator is coping with the tasks laid on him in the best manner.

The value of the total mutual information, contained in some system on the state of one or more other systems in the body of the operator, can be used here as a criterion. The value of the total mutual information on processes taking place in a man are calculated by well-known and widely used formulas in information theory. For two systems A and B, the expression has the form

$$J_{A \leftrightarrow B} = H(A) - H(A/B),$$

where H(A) is the entropy of system A and H(A/B) is the total apparent entropy of system A relative to system B.

It is evident that, for an operator in the state of rest, the value of the total mutual information of the different systems is characteristic of his specific level. In the process of control work by the operator, in the initial stage of training, the value of the total mutual information will be less than at the end of training; in the course of training, it increases to a specific value. Thus, for example, for the case of control of craft orientation, the total mutual information of the alpha rhythm and pulse rate during the first training session was 0.387 binary units and, during the fifth one, 0.551 binary units.

Thus, to sustain a given control process, circulation of a definite quantity of information is necessary. In a closed control system, in one of the "links," which is the operator, the amount of information necessary to sustain a given control process during training will change, since the characteristics of the information receiving, processing and transmission systems, as well as the resistance to interference of the operator, change. /296

However, each of the separately examined criteria for evaluation of the level of training of an operator does not give a fully qualitative evaluation of the work of the operator in a closed control system. Therefore, the necessity arises for development of a generalized criterion for evaluation of the quality of control task execution and training level, which would encompass the entire set of deviations of the coordinates of the controllable process, the quantitative values of the physiological indicators carrying basic data on the condition of the operator and coordination of the work of the different systems of his body, as well as evaluation of the informing processes in a closed system [7].

Features of Selection and Training of Multimember Crews

The number of crew members of an aircraft and their specializations are selected on the basis of detailed analysis and investigation of the tasks of one AC or another, the degree of automation of operations which can be achieved using modern technical resources, as well as with account taken of a number of other factors. In a number of cases, one AC crew member cannot cope with the abundance of flight tasks, and the AC crew must become a multimember one.

It should be taken into account here that social motives and individual psychological singularities and character traits lie at the base of successful collaborative activity of crew members. The contact of the crew members is not restricted to the field of joint work, but it will include a continous stay together under conditions of a small closed association of people. The fact itself of the association of personalities in a group, without fail, generates features of their behavior which were absent in them outside this group. And the problem arises here of /297 the so-called psychophysiological compatibility, i.e., the compatibility of people, as to the singularities of the rhythms and tempos of their psychic activities. The problem of correct selection of people in crews and choice of the crews themselves must be solved first. All people differ from one another in the singularities of their temperaments and natures, frames of mind, interests, needs, opinions, and tendencies for action. However, individual singularities of the operators in crew associations under flight conditions will be "bridged over" by the strong influence of the group. Crew members, by purely human, subjective qualities, must complement one another in the best way, and make up a strong, friendly, efficient group. The groups must be so chosen that the combination of specific people guarantees the most effective accomplishment of the flight mission. These problems must be solved using methods of group psychology in ground, group activity test unit-simulators and trainers.

Groups, united for a common purpose, on the basis of community of interests, mutual sympathies and friendship are called gomphotropic (from the Greek word "gomphein," which means knocked together, nailed together) or psychophysiologically compatible. Not only is a high viability and uniform trend in emotional, voluntary reactions and behaviors characteristics of them, but, which is very important, the capacity for leveling natures, tastes and habits within the group.

On the basis of data existing in contemporary psychology and physiology of higher nervous activity (HNA), on determination of qualities (singularities) of separate individuals (type, nature of HNA, individual psychological peculiarities), the possibility is generated for selection of future crew members,

with subsequent creation of experimental situations -- competitive, conditional-conflict -- to search for ways of reliable development of the qualities of the activity and common existence of two or more persons as a single unity. It is possible to lay down the principles of games theory on the base of research, in which the physiological and psychological aspects are combined in one experiment.

Research must be carried out in the field of crew selection /298
on the psychological aspects of the interactions of people in carrying out interdependent activities, taking place with a deficit or excess of time, as well as the psychic aspects of people living together in prolonged isolation.

In the works of Professor F. D. Gorbov [18, 29], where special arrangements of the homeostat type were used, a group of people, carrying out interdependent work, discovered a structure (intragroup), which was determined by the attitude of the entire group towards strategy (separation of "leader" and "led").

One group can be compared with others with the aid of the homeostat, and it can be seen which of them learns best. Moreover, which members of the group have a tendency towards lagging and assist little in the common improvement of results can be revealed. And a good result can be achieved only by joint efforts.

Such an approach, like in any other test, where competitive, games indicators are used, in no way erodes individual features. On the other hand, they emerge still more distinctly. Having revealed the weak aspects of a given man, individual training must be carried out, in order to determine shortcomings.

Measures and means for increasing stability of the group under extreme conditions should be developed, and questions of the optimum "combination" of the group with automatic machinery or groups of automatic machines should be worked out.

And, finally, the question of construction of computers, simulating the behavior of individuals in carrying out interdependent group activities must be examined, for the purpose of determination of the optimum tactics of the operator in a given group, and such a machine must be used in research on selection of crews of multiplace AC.

In connection with the necessity of AC flights with multiplace crews, together with the division of functions between man and machine, the problem of distribution of functions between crew members is beginning to take an important place. These problems can be solved by use of ground test unit-trainers. Thus, for example, the research of Professor P. K. Isakov, V. A. Popov

and M. M. Sil'vestrov (1967) showed that, by efficient distribution of functions in control of eight coordinates of a process between two operators, the quality of control is increased by 1.5 times over the work of one operator, and the percent of unsuccessful control actions is reduced by half. Crew members, together with technical devices, are sources of data for one another. All this must be taken into account in building a control system and developing methods and means of joint training of operators. /299

It should be taken into account in this case that, with a multimember crew, it is possible to exercise control of an AC and its systems around the clock, which also can lead to definite requirements for development of technical components of AC control systems.

Experience shows that even very experienced and well trained operators can make gross errors in work. Therefore, for particularly important systems, it is inadvisable to use two or more independently working operators. With a sufficiently high degree of reliability of the monitoring-coordinating arrangement, for example, with two inputs, an error can happen only in the case both operators simultaneously committed it. The probability of such coincidence is very low, which considerably increases the overall reliability of operation of the system. The probability of appearance of identical errors in two operators at the same time can be estimated by the formula

$$p_{\tau}=\sum_{s=1}^{N}\left[p_s\sum_{i=1}^{n}\left(p_{si}p'_{si}\right)\right],$$

where p_s is the time necessary for executing operation s; p_{si} is the probability that operator A makes an error of type i in operation s; and p'_{si} is the same, but for operator B.

Calculations confirmed by experiments show that, if there were 116 errors per 10,000 operations in the work of one operator, with simultaneous and independent work of two operators, the number of errors dropped to 37 per 1,000,000 operations, i.e., decreased to 1/300th.

A crew selected for an AC, during the flight training period, will not only work, go through training, engage in physical culture, /300 etc., but pass their time together. Of course, this experiment will not equal the time of a space flight in duration, but lasts a shorter time. However, this time obviously will be sufficient to train the crew and "knock it together," or reveal persons not suitable for a future flight.

Multimember crews of spacecraft open up unrestricted possibilities for the work of astronauts, both in solution of scientific problems and in research in outer space.

CONCLUSION

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We have examined the status of work and results achieved in the field of engineering psychology in aviation and astronautics, as a branch of general engineering psychology.

The material presented, even in such a brief account, indicates, on the one hand, the great successes of Soviet specialists in investigation of man-machine systems in aircraft. On the other hand, it follows from the book that engineering psychology in aviation and astronautics is going through a stage of shaping a new scientific direction, the stage of its formation and accumulation of theoretical and, mainly, experimental data in this field of knowledge. And, of course, a number of important problematic questions are either only mentioned in this book or are completely unresolved and are of interest for subsequent research.

The requirements of the practice of atmospheric and space flights give a basis for asserting that the minimum group of questions presented in the book on research, building and use of "operator-aircraft" systems should by all means be included in the sphere of activity of engineering psychologists in aviation and astronautics.

The collaboration of specialists in various scientific fields will permit solution of urgent problems facing engineering psychology in aviation and astronautics in the future.

We dwell here only on certain, in our opinion, important problems in engineering psychology in aviation and astronautics, which should be solved in the next few years.

First, the efforts of specialists should be directed towards correlation of already existing scientific results, obtained during the conduct of engineering-psychological research. This correlation will make it possible to produce basic documents for designer of AC control systems with human participation, and to develop their "rules for designers."

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The activity of operators in AC control systems must be further studied and investigated more deeply and thoroughly, since many aspects of it are still far from learned (this refers to the capabilities of an operator to receive and process information in flight, determination of the limits of "adaptability" of an operator, connected with his reliability, efficiency, fatiguability, resistance to interference, capacity for observation, in other words, mental and sensory alertness and other things) under extreme conditions and during long flights. Study of this problem will make it possible to begin work in optimization of the man-machine system in AC, from a scientifically grounded position. Since there are large reserves in a man for increasing sensory, motor and intellectual capabilities, there is an important

problem in development of scientifically grounded recommendations for development of sensitivity, short-term memory, rapid thinking and psychomotor qualities.

In principle, the functions of vision, hearing and smell can be strengthened, and the sensing of necessary sensations, electrical signals, ionizing radiation, magnetic field, by the operator also can be provided.

The use of devices converting electromagnetic radiation in the invisible ranges of the spectrum into a visible light spectrum makes practicable the production of visual images of objects emitting ultraviolet, infrared, gamma and radio radiation.

To expand the capabilities of visual perception, the development and use of technical devices, transmitting a visual image to the operator with a necessary delay, the use of special light filter-screens, retaining a rapidly moving image which passes out of the field of vision for a certain time, is attractive.

Similar problems arise with respect to improvement of the auditory function. Transforming devices can convert ultra and /303
infrasound oscillations into normal ones, which can be perceived by the human ear, as well as facilitate long storage of a specific sound image. The idea of regulation of sound intensity can be accomplished by the same principle. High intensity sounds are attenuated by passive filters (absorbers, headphones, helmets) or by active devices, to an acceptable level, both with respect to intensity as well as distinctness of the acoustical signal perceived. For protection from brief, high intensity acoustical impacts, technical devices automatically overlapping the sound wave path are necessary.

Improvement of the olfactory function serves the purpose of revealing certain important components of a closed ecological system , certain of which are not smelled at all by a man. For this purpose, gas analyzers, recording the simultaneous presence of several chemical substances and signalling this to man through the eyes and ears, by means of the use of "dangerous" olfactory substances (mercaptans) or even electrical communications to a peripheral nerve, are used.

New types of perceptions can be created with the aid of technical resources. An "electrical sense" is simulated by means of application of surface electrodes in the region of an afferent nerve. Significant information, coming in through these electrodes can be coded in time and space, and the intensity of stimulation can be established below the pain threshold.

The use of medicinal substances, which can change the stimulus threshold in one direction or another and affect the interactions

of the analyzers is a real possibility for improvement of the sensory functions.

Improvement in the motor functions of man is completely achievable now, owing to the development of prosthetics. Casings, tightly embracing a limb, can assist in "managing" the limb, giving the necessary strength to movement. Such a casing is required for control during spacecraft maneuvers, connected with great G-forces , as well as for moving and maintaining the body position on the surface of a planet with a high gravity. The use /304 of casings can also provide an improvement in movement coordination and decrease in shaking.

Reinforcement of the muscular activity of a man can be achieved by transmission of bioelectric signals from the afferent nerves and muscles to the actuating control system. Biopotentials can be drawn from the muscles of the forearm or the eye by means of a contact ring, and even from the cerebral cortex and descending pyramidal paths, for the purpose of decreasing the latent period of the motor reaction.

Still another area directly connected with the problems of engineering psychology in aviation and astronautics cannot be passed by in silence.

During use of a space suit, efficiency and mobility of a pilot or astronaut is reduced, especially at increased pressure within the space suit. Therefore, in a number of countries, the effort is being made to increase the physical capabilities of man, by means of use of electromechanical devices, capable of duplicating and strengthening the operation of his support-motor apparatus.

A so-called exoskeleton (external skeleton) has already been made in the USA. Its purpose is to relieve the support-motor apparatus of a man and simultaneously increase the strength of the arms and trunk. The hypothesis is being stated that a man can create the force necessary for lifting a 450 kg load, with the aid of the exoskeleton.

It is known that work is being done abroad to create a machine which could read records made by a man or perceive instructions given verbally, i.e., the problem of automatic recognition of human speech by a machine is being solved. Solution of this problem permits direct control of the various processes and systems during flight in an AC or during landing on a planet, by means of giving verbal commands, entering input data by voice into a computer and, in this manner, transmitting commands to machines, eliminating an intermediate operator.

By solution of this complicated problem, a machine may be compelled to help a man formulate a problem, i.e., give him help

in his thinking, in a way similar to that by which a machine now helps solve problems formulated by man. In this manner, man and machine will jointly participate in working out solutions and in control of complicated situations, without a rigid dependence upon a previously assigned program. /305

Work is forthcoming on the deeper study of the information properties of the various analyzers and in the great "implication" in the actions of such operator analyzers as the tactile (touch).

Engineering pscyhology in aviation and astronautics must "get into" mathematical interpretation of various "characteristics" of an operator, such, for example, as teachability, adaptability, prediction, training, object identification ability, throughput capacity and many others, which would permit synthesis and optimization of semiautomatic operator-AC systems, similar (or analogous) to fully automatic control systems.

In engineering psychology in aviation and astronautics, the tendency to change from examination of only one, "the human link," to investigation of operator-AC systems as a whole must be strengthened; the problem of simulation (creation of theoretical-information models) of the activity of an operator, not by unambiguously determined input actions, but by probability information at the input, must be solved; the subjective qualities of the operator and his emotional state must be reflected in the models; the change in the behavior of an operator under circumstances when the potentials of the signals carrying information change with time must be studied.

Problems of the psychological choice of operators, according to personal qualities, taking account of individual features of the nervous system, emotional stability and capacity for work under extreme conditions, also must be solved. This problem of preliminary development and selection of persons, capable of effectively working in a control system, by his physiological, psychological and anthropological parameters, is one of the most urgent problems in general engineering psychology. There still is not a single point of view among the specialists in connection with the principles and methods of selection. The task is complicated by the fact that, as a rule, selection and test methods are calculated on the "average" man, proceeding from general patterns of psychic activity of the "average" man, but the selection itself is made on the basis of individual features. /306 While coordination of the characteristics of man and machine rests on data of the "average" man, the likelihood of choice remains unacceptably large. The screening out of operators according to ascertainment of their unsuitability leads to sad consequences: the more complicated the system, the longer the road to training the operator and the more important his errors. Therefore, the individuality

of a man, his personality, must remain the object of engineering-psychological research, applicable to conditions of activities of pilots and astronauts. Among the important problems of engineering psychology in aviation and astronautics also are the study of group activity of operators in the control process, interconnected by specific psychological and functional relationships, an increase in their independence and the problem of psychological compatibility.

We consider that, with further development of new technical resources, the question of "replacement" of man by machines will not come up again. Then, as now, man will not be set against technology, as if there were no "wisdom" or "intellectual" growth. The questions then will be how best to adapt this technology to the psychophysiological capabilities of the operator, how best to use it, not as a counterbalance to man, but for man, how to match the operator to the "supermachine," for the purpose of optimization of the "operator-aircraft" system of the future. There are very tempting and interesting prospects in the future for engineering psychology in aviation and astronautics. And here, one must look, not backward, but ahead, not divert engineering-psychological research, waiting for technology to "displace" man, but to intensively develop further research.

Thus, the future is not to the machine, to this product of human intelligence and hands, but to the man-machine system, headed by man, by this integration "element" of the system, in whom a multiplicity of diverse functions is concentrated. Therefore, it is more nearly correct to speak, not of the potentialities of future machines, but of the capabilities of the operator, creating these machines and having them at his disposal The use of optimized man-machine systems must be aimed for, creating conditions for the best work of the operator in these systems, with the minimum necessary load, which would permit use of the operator for carrying out control functions of a higher order than control proper (tracking, regulating). It is most likely here that the planned shift should be sustained, in responsibilities of an operator in an AC, especially in spacecraft, in the direction of monitoring and repair of systems, in the direction of extracting new data in the course of operation of the system and production of the most recent data on the basis of it. /307

We have dwelt only on certain general problematic questions of engineering psychology in aviation and astronautics. The tasks of engineering psychology will increase, in proportion to increase in complexity of tasks facing aviation, and in proportion to the expansion of programs for mastery of space and increase in complexity of control systems and items of equipment in the AC cockpit. Existing results of successful work in engineering psychology in aviation and space permit it to be hoped that the purposeful work of psychologists, doctors, engineers, designers, pilots and astronauts will assist in more effective solution of the problems of interaction of an operator in such a complicated biomechanical system as a piloted aircraft.

REFERENCES /308

1. Adams, D., Inzhenernaya psikhologiya, [Engineering Psychology], Progress Press, Mowcow, 1964.

2. Boyko, Ye.I., Vremya reaktsii cheloveka, [Reaction Time of Man], Meditsina Press, Moscow, 1964.

3. Boyko, N. I. et al., K voprosu ob ispol'zovanii elektronno-luchevykh trubok v kachestve mnogofunktional'nykhindikatorov, [The Utilization of Cathode Ray Tubes as Multifunction Displays], Central Scientific Research Institute of Information and Technical-Economic Research in Instrument Making, Automation Resources and Control Systems, Moscow, 1967.

4. Belyaev, P. I. et al., "Some dynamic characteristics of the operator while tracking under spaceflight conditions in the craft 'Voskhod-2," Kosmicheskiye issledovaniya 4 (1), Nauka Press, Moscow, 1966.

5. Borshchevskiy, I. Ya. et al, Obshchaya vibratsiya i yeye vliyaniye na organizm cheloveka, [Common Vibrations and their Effect on the Human Body], Medgiz Press, Moscow, 1963.

6. Borshchevskiy, I. Ya.,Kuznetsov, V. S., and Lapayev, E. V., "Standardization of aviation noise,"Voyenno-meditsinskiy zhurnal, No. 11 (1967).

7. Bulat, A. A. et al., "Integral method of evaluation of training of operators in control systems," in the collection: Sistema chelovek i avtomat, [Man and Automatic Machine System], Nauka Press, Moscow, 1965.

8. Buyanov, P. V. et al., "Prolonged hypokinesia as a factor changing the functional condition of the cardiovascular system of a healthy man," in the collection: Problemy kosmicheskoy meditsiny, [Problems of Space Medicine], Minzdrav SSSR, Moscow, 1966.

9. Vasil'yev, P. V., and Kotovskaya, A. R., "Physiological reactions of man under the influence of G-forces during space flights," Doklad na XVI Mezhdunarodnom astronavticheskom kongresse [Report to the XVI International Astronautical Congress], Athens, 1965.

10. Volkov, A. A. et al., "The structure of a command signal and the psychophysiological capabilities of an operator in control under overload conditions," in the collection: Sistema chelovek i avtomat, [Man and Automatic Machine System], Nauka Press, Moscow, 1965.

11. Volkov, A. A. and Zav'yalov, Ye.S., "An astronaut looks at the earth," Aviatsiya i kosmonavtika No. 2 (1965).

12. Volynkin, Yu. M. and Zarakovskiy, G. M., "Psychology and a Pilot's Work," Aviatsiya i kosmonavtika, No. 10 (1966).

13. Woodson, U., and Conver, D., Spravochnik po inzhenernoy psikhologii dlya inzhenerov i khudozhnikov-konstruktorov, [Handbook of Engineering Psychology for Engineers and Artist-Designers], Mir Press, Mowcow, 1968.

14. Gerathewohl, Z., Psikhologiya cheloveka v samolete, [The Psychology of Man in an Aircraft], Foreign Literature Publishing House, Moscow, 1956. /309

15. Genin, A. M., and Sorokin, P. A., "Prolonged restriction of mobility as a model of the effect of weightlessness on the human body," in the collection: Problemy kosmicheskoy biologii, [Problems of Space Biology], Vol. 13, Nauka Press, Moscow, 1969.

16. Genin, A. M., and Pestov, I. D., "Against the adverse effects of weightlessness," Aviatsiya i kosmonavtika, No. 3 (1972)

17. Gozulov, S. A., and Frolov, N. I., "Evaluation of muscular efficiency of man after the action of impact overloads," in the collection: Problemy kosmicheskoy meditsiny, [Problems of Space Medicine], Minzdrav SSSR, Moscow, 1966.

18. Gorbov, F. D., "Space psychology," in the collection: Kosmicheskaya biologiya i meditsina, [Space Biology and Medicine], Nauka Press, Moscow, 1966.

19. Gromov, A. V. and Kuznetsov, V. S., "Indivual Noise Protection Means," Aviatsiya i kosmonavtika, No. 5 (1968).

20. Gurovskiy, N. N. et al, "Trainers for training of astronauts for professional activity in control of a spacecraft and its systems," in the collection: Problemy kosmicheskoy biologii [Problems of Space Biology], Vol. 4, Nauka Press, 1965.

21. Denisov, V. G. and Lopatin, R. N., Pilotazhno-navigatsionnyye pribory, [Flight-Navigation Instruments], Moscow, Voyenizdat Press, 1962.

22. Denisov, V. G. and Lopatin, R. N., Letchik i samolet, [Pilot and Aircraft], Moscow, Oborongiz Press, 1962.

23. Denisov, V. G., "Some aspects of the problems of the combination of man and machine in complex control systems," in

the collection: Problemy kosmicheskoy biologii, [Problems of Space Biology], Vol. 2, Nauka Press, 1962.

24. Denisov, V. G., Navigatsionnoye oborudovaniye letatel'nykh apparatov, [Aircraft Navigation Equipment], Oborongiz Press, Moscow, 1963.

25. Denisov, V. G., Kosmonavt letayet...na Zemle [The Astronaut Flies... on Earth], Moscow, Mashinostroyeniye Press, 1964.

26. Denisov, V. G., "Basic problems in the engineering psychology of space flight ," in the collection: Problemy kosmicheskoy psikhologii, [Problems of Space Psychology], Vol. 3, Nauka Press, 1964.

27. Denisov, V. G., Onishchenko, V. F., and Yazdovskiy, V. I., "Psychophysiological capabilities of astronauts in control of a spacecraft and its systems (engineering psychology)," in the book: Kosmicheskaya biologiya i meditsina, [Space Biology and Medicine], Nauka Press, Moscow, 1966.

28. Denisov, V. G., and Onishchenko, V. F., "Characteristics of data coding in piloted aircraft," in the collection: Inzhenernaya psikhologiya v priborostroyenii, [Engineering Psychology in Instrument Making], Central Scientific Research Institute of Information and Technical-Economic research in Instrument Making, Automation Resources and Control Systems.

29. Denisov, V. G., and Onishchenko, V. F., Shagi sredi zvezd. (V polete chelovek i avtomaty), [Steps Towards the Stars (Man and Automatic Machines in Flight)], Znaniye Press, Moscow, 1970.

30. Denisov, V. G., and Onishchenko, V. F., "The effect of data coding systems on the work of an operator," in the collection: Problemy inzhenernoy psikhologii, [Problems in Engineering Pyschology], Nauka Press, 1967.

31. Denisov, V. G., Kuz'minov, A. P., and Onishchenko, V. F., "Investigation of reliability of operation of an operator in the man-machine system under conditions of change in the gaseous environment," Proceedings of the All-Union Society of Psychologists, USSR, Vol. 3, Academy of Psychological Sciences, Russian SFSR, Moscow, 1968. /310

32. Denisov, V. G., Znakom'tes': ergonomika, [Get Acquainted With Ergonomics], Znaniye Press, Kiev, 1971.

33. Derevyanko, Ye. A., Kuznetsov, V. G., and Myl'nikov, V. G., "Some means of experimental study of operator reliability," in the collection: Inzhenernaya psikhologiya v priborostroyenii, [Engineering Psychology in Instrument Making], Central Scientific Reserach Institute of Information and Technical-Economic Research in Instrument Making, Automation Resources and Control Systems, Moscow, 1967.

34. Yeliseyev, A. S. et al. "Indicators of mismatch in manual control systems with low controlling action effectiveness," in the collection: Problemy inzhenernoy psikhologii v priborostroyenii, [Problems of Engineering Psychology in Instrument Making], Central Scientific Research Institute of Information and Technical-Economic Research in Instrument Making, Automation Resources and Control Systems, Moscow, 1967.

35. Zharov, S. G. et al., "Condition and efficiency of man under conditions of a prolonged stay in a spacecraft mock-up," in the collection: Problemy kosmicheskoy biologii, [Problems of Space Biology], Vol. 7, Nauka, Moscow, 1967.

36. Zabalova, N. D. et al., "Improvements in flight parameter displays as a condition of increasing reliability of the 'pilot-aircraft' system," in the collection: Inzhenernaya psikhologiya v priborostroyenii, [Engineering Psychology and Instrument Making], Central Scientific Research Institute of Information and Technical-Economic Research in Instrument Making, Automation Resources and Control Systems, Moscow, 1967.

37. Zav'yalov, Ye. S., and Mel'nik, S. G., "Activity of a human operator in the tracking mode under the influence of certain factors of space flight," Kosmicheskaya biologiya i meditsina, No. 3, Meditsina Press, 1967.

38. Zarakovskiy, L. M., "Flight and psychology: time deficit and pilot thinking," Aviatsiya i kosmonavtika, No. 12, 1966.

39. Zinchenko, V. P., and Smolyan, G. L., Chelovek i tekhnika, [Man in Technology], Znaniye Press, Moscow, 1965.

40. Ivanov, D. I., and Khromushkin, A. I., Sistemy zhizneobespecheniya cheloveka pri vysotnykh i kosmicheskikh poletakh, [Human Life Support Systems in High-Altitude and Space Flights], Mashinostroyeniye Press, Moscow, 1968.

41. Ivanov, Ye. A., Popov, V.A., Khachatur'yants L. S., "Orientation and activity in unsupported space," Aviatsiya i kosmonavtika, No. 7, 1966.

42. Inzhenernaya psikhologiya za rubezhom, [Engineering Psychology Abroad], Progress Press, Moscow, 1967.

43. Inzhenernaya psikhologiya v primenenii k proyektirovaniyu oborudovaniya, [Engineering Psychology Applied to Equipment Design], translation from English, Mashinostroeyeniye Press, Moscow, 1971.

44. Ioseleani, K. K., "Complex psychic processes under the conditions of vibration action, Voyenno-meditsinskiy zhurnal, No. 6, 1965.

45. Isakov, P. K., Popov, V. A., and Khachatur'yants, L. S., "Evaluation of astronaut efficiency (from data of the flights of Voskhod-1 and 2)," Report to the XVI International Astronautical Congress, Athens, 13-18 September, 1965.

46. Isakov, P. K., Popov, V. A., Sil'vestrov, M. M., "Problems of human reliability in spaceship control systems," in the collection: Problemy kosmicheskoy biologii, [Problems of Space Biology], Vol. 7, Nauka Press, Moscow, 1967. /311

47. Isakov, P. K. et al., Teoriya i praktika aviatsionnoy meditsiny, [Theory and Practice of Aviation Medicine], Meditsina Press, Moscow, 1971.

48. Karpov, Ye. A., "Psychophysiological analysis of activity as a criterion for special medical training of the Voskhod-2 spaceship crew," Kosmicheskiye issledovaniya 4 (3), Nauka Press, 1966.

49. Kas'yan, I. I., Kopanev, V. I., and Yazdovskiy, V. I., "Weightlessness," in the collection: Kosmicheskaya biologiya i meditsina, [Space Biology and Medicine], Nauka Press, 1966.

50. Kitaev-Smyk, L. A. and Zverev, A. T., "The effect of brief weightlessness and the combined action of weightlessness, angular and Coriolis accelerations on certain work functions of an operator," in the collection: Sistema chelovek i avtomat, [Man and Automatic Machine System], Nauka Press, 1965.

51. Korobkov, A. V., "Development and maintenance of high level of motor reactions in space flights," in the collection: Aviatsionnaya i kosmicheskaya meditsina, [Aviation and Space Medicine], AMN SSSR, Moscow, 1963.

52. Kosenkov, M. M., and Kuz'minov, A. P., "Some results and problems of observation under space flight conditions," Report to 3rd International Symposium on Bioastronautics, San Antonio, Texas, 1964.

53. Kuz'minov, A. P., Onishchenko, V. F., and Sil'vestrov, M. M., "Investigation of efficiency of man connected with systems control activity," in the collection: Materialy 2 Vsesoyuznogo s"ezda Obshchestva psikhologov SSSR, [Materials of 2nd All-Union Congress of the Society of Psychologists SSSR], Academy of Psychological Sciences, Russian SFSR, Moscow, 1963.

54. Kuz'minov, A. P., Oninshchenko, V. F., Sil'vestrov, M. M., "Retention of skills in data transmission under conditions of prolonged isolation," in the book: Problemy kosmicheskoy biologii, [Problems of Space Biology], Vol. 3, Nauka Press, Moscow, 1964.

55. Kuz'minov, A. P., Onishchenko, V. F., and Sil'vestrov, M. M., "Investigation of the working activity of astronauts," in the collection: Vtoroy gruppovoy kosmicheskiyi polet, [Second Group of Space Flights], Nauka Press, Moscow, 1965.

56. Kuz'minov, A. P. et al., "Comparative study of perception of digital indicator readings," in the collection: Inzhenernaya psikhologiya v priborostroyenii, [Engineering Psychology in Instrument Making], Central Scientific Research Institute of Information and Technical-Economic Research in Instrument Making, Automation Resources and Control Systems.

57. Leonov, A. A., and Lebedev, V. I., Psikhologicheskiye osobennosti deyatel'nosti kosmonavtov, [Psychological Features of Astronaut Activities], Nauka Press, Moscow, 1971.

58. Leont'yev A. M., Inzhenernaya psikhologiya za rubezhom, [Engineering Psychology Abroad], Progress Press, Moscow, 1967.

59. Lomov, B. F., Chelovek i tekhnika, [Man and Technology], Sov. radio Press, Moscow, 1966.

60. Nebylitsyn, V. D., "Reliability of operator work in a complex control system," in the collection: Inzhenernaya psikhologiya, [Engineering Psychology], Moscow State University, 1964.

61. Onishchenko, V. G., Volkov, A. A., and Mel'nik, S. G., "Use of the polyeffector method for evaluation of psychophysiological capabilities of an operator in the 'man-machine' system," in the collection: Problemy inzhenernoy psikhologii, [Problems in Engineering Psychology], Vol. 4, Academy of Psychological Sciences, Russian SFSR, Leningrad, 1962. /312

62. Onishchenko, V. F., "Certain forms of sluggish exaltation of alpha rhythm under extreme conditions," in the book: Elektrofiziologiya tsentral'noy nervnoy sistemy, [Electrophysiology of the Central Nervous System], Metsniyereba Press, Tbilisi, 1966.

63. Onishchenko, V. F., "Certain changes in EEG of an operator during work processes in the 'man-machine' system" in the book: Elektrofiziologiya tsentral'noy nervnoy sistemy, [Electrophysiology of the Central Nervous System], Metsniyereba Press, Tbilisi, 1966.

64. Onishchenko, V. F., "Investigation of skill persistence in control systems under conditions of many days of hypodynamia," Proceedings of the 3rd All-Union Congress of the Society of Psychologists SSSR, Vol. 3, Academy of Psychological Sciences Russian SFSR, Moscow, 1968.

65. Platonov, K. K., Chelovek v polete, [Man in Flight], Voyenizdat Press, 1957.

66. Ponomarenko, V. A., Avayev, A. L., and Zavalova, N. D., "Principles of coding of signals of automatic control failures in a time deficit," in the collection: Inzhenernaya psikhologiya v priborostroyenii, [Engineering Psychology in Instrument Making], Central Scientific Research Institute of Information and Technical-Economic Research in Instrument Making, Automation Resrouces and Control Systems, Moscow, 1967.

67. Popov, V. A., Rozanov, Yu. A., and Sil'vestrov, M. M., "Information model of dynamics and spatial orientation of astronauts outside the ship," Report to the 17th International Astronautical Congress, Madrid, 9-15 October, 1966.

68. Popov, V. A., and Boyko, N. I., "Vision in space flight," Aviatsiya i kosmonavtkia, No. 7 (1967).

69. Pudik, P. A., Psikhologiya [Psychology], Uchpedgiz Press, 1958.

70. Sergeyev, G. A., Pavlova, L. P., and Romanenko, A. F., Statisticheskiye metody issledovaniya elektroentsefalogrammy cheloveka, [Statistical Methods of Examination of Electroencephalograms of a Man], Nauka Press, Moscow, 1968.

71. Stepantsov, V. I., and Yeremin, A. V., "Biomechanics of man in an unsupported position (weightlessness)," Kosmicheskiye issledovaniya 7 (6), Nauka Press, Moscow, 1969.

72. Stevens, S. Eksperimental'naya psikhologiya, [Experimental Psychology], translation from English, Mir Press, 1962.

73. Khachatur'yants, L. S., "Physiology of space work," Meditsinskaya sestra, No. 1 (1967).

74. Shamrov, P. G., "Evaluation of psychophysiological capabilities of an operator in the 'man-machine' system," in the collection: Problemy inzhenernoy psikhologii [Problems in Engineering Psychology], Vol. 4, Academy of Psychological Sciences, Russian SFSR, Leningrad, 1966.

75. Shteynbukh, K., Chelovek i avtomat, [Man and Automatic Machine], Sovetskoyeradio Press, Moscow, 1967.

76. Yuganov, Ye. M., Kas'yan, I. I., and Kopanev, V. I., "Jet engine under weightless conditions," in the collection: Izvestiya AN SSSR, [USSR Academy of Sciences News], biological series No. 5 (1964).

77. Yuganov, Ye. M., Krylov, Yu. V., and Kuznetsov, V. S., "The problem of standardization of noises in spacecraft cabins during prolonged flights," Report to 16th International Astronautical Congress, Athens, 13-18 September, 1965. /313

78. Yuganov, Ye. M., Krylov, Yu. V., and Kuznetsov, V. S., "Forming an optimum acoustical environment in spacecraft cabins," in the collection: "Izvestiya AN SSSR, [USSR Academy of Sciences News], biological series, No. 1 (1966).

79. Yazdovskiy, V. I. et al., "Sensorimotor coordination under conditions of prolonged weightlessness on an actual space flight," in the collection: Aviatsionnaya i kosmicheskaya meditsina, [Aviation and Space Medicine], Academy of Medical Sciences, USSR, Moscow, 1963.

80. Chatelier, F., and Gibert, A., "Physiopathological effects," Rev corps sante armees, mer, air 10 (6) (1969).

81. Chemin, P., "Ergonomy and astronautics," Rev. franc. aff. social 23 (4) (1969).

82. Clark, N., "Human acceleration effects for rocket flight," Amer. Rocket Soc. 804 (1959).

83. Connor, R. W., and Smith, E. A., "Emphasis on survival in the design of interplanetary vehicles," Ballistic Missile and Space Technol., Vol. 4, New York-London, Acad. Press, 1960, pp. 315-337.

84. Drinkwater, B. L., "Pilot performance during periods of anticipatory physical threat stress," Aerospace Med. 39 (9), 994-999 (1968).

85. Fraser, T. M., Hoover, G. N., and Ashe, W. F., "Tracking performance during low frequency vibration," Aerospace Med. 32 (9), 829-835 (1961).

86. Gerathewohl, S. J., "Work proficiency in the space cabin simulator," Aerospace Med. 30 (10), 722-735 (1959).

87. Greening, C. P., "Coriolis effects on operator movements in rotating vehicles," Aerospace Med. 33 (5), 579-582 (1962).

88. Grodsky, M. A., and Sorkin, R. D., "Man's contribution to an operational space station conept," Aero/Space Engng. 19 (5), 80-81 (1960).

89. Hines, W., "Is man qualified in space?" Bioscience 18 (11) 1968.

90. Iampietro, P. F., "Complex performance during exposure to high temperatures," Aerospace Med. 40 (12), 1331-1335, (1969).

91. Lamb, L. E., and Stevens, P. M., Hypokinesia secondary to chair rest from 4 to 10 days," Aerospace Med. 36 (8) (1965).

92. Loats, H. L., and Mattingly, G. S., "Weightless as a key to orbital man-machine experimentation," AIAA Papers, No. 71-850, 1971.

93. Rushton, W. A., Effect of humming on vision," Nature 216 (5121) (1967).

94. Still, E. W., "High altitude chambers and pressure suits and their part in manned flight to the Moon," Journal of the British Interplanetary Society 17 (8), 239-276 (1960). /314

95. Wortz, E. C., "Effects of reduced gravity environment on human performance," Aerospace Med. 39 (9), 963-965 (1968).